Recent advances in drilling hybrid FRP/Ti composite: A state-of-the-art review

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A B S T R A C T

Hybrid composite stack, especially FRP/Ti assembly, is considered as an innovative structural configuration for manufacturing the key load-bearing components favoring energy saving in the aerospace industry. Several applications require mechanical drilling for finishing hybrid composite structures. The drilling operation of hybrid FRP/Ti composite, however, represents the most challenging task in modern manufacturing sectors due to the disparate natures of each constituent involved and the complexity to control tool–material interfaces during one single cutting shot. Special issues may arise from the severe subsurface damage, excessive interface consumption, rapid tool wear, etc. In this paper, a rigorous review concerning the state-of-the-art results and advances on drilling solutions of hybrid FRP/Ti composite was presented by referring to the wide comparisons among literature analyses. The multiple aspects of cutting responses and physical phenomena generated when drilling these materials were precisely addressed. A special focus was made on the material removal modes and tool wear mechanisms dominating the bi-material interface consumption (BIC) with respect of investigating strategies used. The key conclusions from the literature review were drawn to point out the potential solutions and limitations to be necessarily overcome for reaching both *(i)* enhanced control of drilling operation, and *(ii)* better finish quality of FRP/Ti parts.

Keywords:
FRP/Ti composite
Drilling force
Cutting mechanism
Drilling-induced damage
Wear mechanism
High-quality drilling

Contents

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Nomenclature

a	dimensional constant
A_{del}	delamination area
A_{nom}	nominal area of the drilled hole
b	dimensional constant
BCC	high-temperature β phase
D	drill diameter
D_{11}	coefficients for the bending stiffness of FRP laminate
D_{12}	coefficients for the bending stiffness of FRP laminate
D_{22}	coefficients for the bending stiffness of FRP laminate
D_{66}	coefficients for the bending stiffness of FRP laminate
D_c	equivalent bending stiffness coefficient of FRP laminate
D_{max}	maximum diameter of the delamination area
D_{nom}	nominal hole diameter
D_{RAT}	two-dimensional delamination factor
E	elastic modulus
f	feed rate
F_d	one-dimensional delamination factor
F_{da}	adjusted delamination factor
FRP → Ti	drilling from FRP phase to Ti phase
G_{IC}	critical energy release rate in fracture mode I
h	dimensional constant
HCP	low-temperature α phase
n	spindle speed
P_{ch}	concentrated force
q	uniformly distributed force
R_a	average surface roughness
R_z	average peak to valley height
R_t	peak to valley height
T	material thickness
Ti → FRP	drilling from Ti phase to FRP phase
t_m	multi-tool–work interaction time
v_c	cutting speed
WC	tungsten carbide
α	used weight in F_{da}
α_r	tool rake angle
β	used weight in F_{da}
θ	fiber orientation
λ	thermal conductivity
ν	Poisson's ratio
ϕ	drill point angle
ψ	drill helix angle
ξ	proportional coefficient

Abbreviation

Al	aluminum
BIC	bi-material interface consumption
BUE	built-up edge
CVD	chemical vapor deposition
CTF	critical thrust force
doc	depth of cut
FRP	fiber reinforced polymer
HSS	high-speed steel
MQL	minimum quantity lubrication
PCD	polycrystalline diamond
PVD	physical vapor deposition
TEC	thermal expansion coefficient
Ti	titanium

1. Introduction

In modern aerospace industry, the manufacturing sectors are developing hybrid composite stacks to enhance the characteristics of new-generation structures and to continuously motivate the development of mechanical assemblies favoring energy saving. Material made of multi-layers of fiber reinforced polymer (FRP) and metal alloy (e.g., titanium alloy, aluminum alloy, etc.) is a typical example of hybrid composite configuration. The benefits of such composite-to-metal alliance arise from the ability to combine resistance and to enhance specific characteristics without significantly increasing the part weight [1–5]. As such, the hybrid composite stack provides enhanced material properties so that the attractive aspects of each constituent material are utilized and their weaknesses are avoided. The key advantages to deliver energy saving and to improve system performance have made the material a good candidate to substitute standard composites and single metal alloys in various industrial applications. Aircraft structures subjected to high thermo-mechanical stresses are successfully fabricated with these materials. The wing-fuselage connection of the new-generation Boeing 787 Dreamliner is a typical application.

Among the available configurations of hybrid composite stacks, FRP/Ti coupling (FRP/Ti, FRP/Ti/FRP, Ti/FRP/Ti), was identified as the most popular one due to its best combination of metallurgical and physical properties including high strength-to-weight ratio and excellent corrosion/erosion resistance [1–8]. In particular, the FRP/Ti stack exhibits a high strength-to-weight ratio with yield strength as high as 830 MPa and a density of roughly 4 g/cm^3 [9]. Moreover, the FRP/Ti coupling yields also many advantages over the FRP/Al coupling in several aspects such as reduced galvanic corrosion, improved specific strength, etc. [10,11]. Such superior properties ensure its key application focused on manufacturing the key load-bearing components of large commercial aircrafts in the modern aerospace industry.

With regard to its assembly, the stacked FRP and Ti phases are usually joined by mechanical fastening technique, which is the principal method currently used for structural component assembly with the advantages of good reliability, easy detachability and convenient inspectability [12–15]. It should be noted that in real FRP/Ti configurations, some of them have existed an adhesive layer to combine each phase together, and some others are separated individually without any adhesive layer. Nevertheless, the mechanical fastening is an essential requirement to ensure the tight joining of such multi-phase material. Since the assembly process demands a large number of holes to be drilled out, the good control of drilling becomes crucial for achieving undamaged parts. In addition, the FRP and Ti phases are often stacked together prior to being drilled out in single-shot time. This minimizes the positional errors and favors tight tolerances in actual production.

Although drilling FRP/Ti stack in single-shot time is beneficial from a manufacturing standpoint [1–3,9], the processing task still remains challenging because of the large disparity in properties of involved phases. For instance, FRP is an anisotropic material consisting of two distinct constituents (reinforcing fiber and polymer matrix) with neatly different properties. The reinforcing fiber exhibits elastic-brittle behavior and poor thermal conductivity while the polymer matrix shows ductile behavior. As for the metallic phase, the Ti alloy exhibits poor thermal conductivity, low elastic modulus, and high chemical affinity to most used tool materials in machining. These characteristics usually lead to severe abrasive wear and edge chipping for FRP-phase cutting [16–19] and serious chip adhesion, intense flank wear and premature tool failure in Ti-phase machining [20,21].

Technically, the key challenges in FRP/Ti stack drilling may arise from the poor conditions of the multi-tool–work interaction associated with the disparate natures of stacked constituents. The non-compliance between the tool–metal interface, on one hand, and the tool–composite interface, on another hand, induces local interface discontinuities and, hence, affects the cutting behavior. These discontinuities present the major obstacles to be overcome for better controlling of the cutting conditions and proper selection of the tool–work configuration, which consists of the main scientific and technological challenge. Drilling FRP/Ti stack usually produces severe hole damage including induced delamination, matrix degradation, fiber pullout, exit burr defect, etc., which leads to a great deal of rejections in the actual production. The drilling action also affects the tool life because of the rapid tool wear. As such, hybrid composite stack drilling becomes a highly-cost and time-consuming task among the manufacturing community.

Although the FRP/Ti assembly has been utilized in industries for several decades, theoretical and experimental results concerning its mechanical/physical responses in drilling are still significantly understudied. Despite a variety of review papers available on interpreting the machining physics of standard FRPs and single titanium alloys [7,22–30], reviews concerning the multi-physical issues of drilling the two stacked constituents (FRP/Ti) are rarely reported. Recently, Krishnaraj et al. [31] had provided a comprehensive review on drilling of multi-material stacks. The review work made more efforts to review the drilling behavior of separated constituents (composite laminate, titanium alloy and aluminum alloy) rather than to focus on the stacked composite drilling behavior. Since the scientific advances in this field still continue to develop, pointing out a state-of-the-art involving the research topic can provide a beneficial guide for both current and future work. This is the key incentive that motivates the current review work to treat rigorously the most significant achievements gained in the bi-material drilling. The multi-physical aspects involved in hybrid FRP/Ti drilling have been precisely addressed based on the literature analyses. Moreover, the potential strategies and methods aiming to high-quality drilling of hybrid FRP/Ti stacks are also reviewed.

2. Material properties and characterization

2.1. FRP composite phase

Advanced composite material, such as fiber reinforced polymer (FRP), has been broadly employed in structural components due to its attractive properties including high specific stiffness, high strength, and high corrosion resistance. The main family of FRP laminates widely used in industries includes CFRP (carbon fiber reinforced polymer) laminate [32], GFRP (glass fiber reinforced polymer) laminate [33], and fiber metal laminate (FML) [34]. Among them, the CFRP and GFRP laminates are by far the most-used constituents in a hybrid composite configuration in view of their excellent mechanical properties. The primary constituents in the FRP phase are reinforcing fibers (e.g., carbon, glass, etc.) and polymer matrices (e.g., thermoplastic resin, thermosetting resin, etc.). The fiber is characterized by lightweight, stiff and strong, which contributes to enhancing mechanical and tribological properties of the material system, while the polymer matrix binds the fibers together, providing load transfer and structural integrity. The mechanical properties of FRP laminates critically depend on the fiber layup along the epoxy matrix. For example, the unidirectional fiber-orientation prepreg ply (UD-ply) shown in Fig. 1(a) [27,35] exhibits quite-different mechanical properties along/in perpendicular to the fiber direction, i.e., maximum stiffness/strength along the fiber direction and minimum properties in perpendicular to the fiber direction. However, a bi-directional fiber-orientation prepreg ply (woven-ply) presented in Fig. 1(b) [27,35] almost has the maximum stiffness/strength along the both directions. For multi-orientation FRP laminates, they are usually made by bonding many prepreg plies together at different fiber

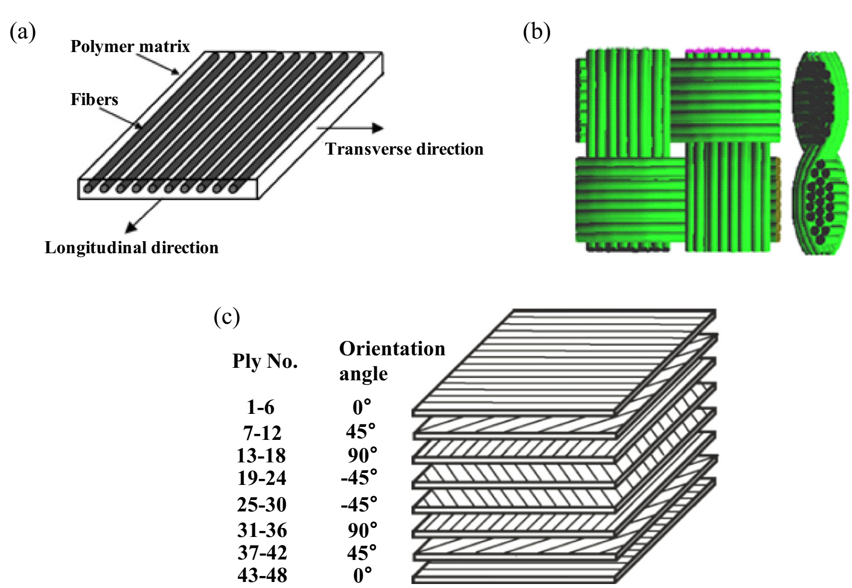


Fig. 1. Schematic illustration of the commonly-used FRP composite structures: (a) UD-ply laminate [27,35], (b) woven-ply laminate [27,35], and (c) multi-orientation laminate following the quasi-isotropic stacking sequence of $[0°/45°/90°/-45°]_{6S}$ [27,36].

orientations (cross-ply) to gain enhanced properties. Fig. 1(c) shows the scheme of one type multi-orientation FRP laminate following the quasi-isotropic stacking sequence of $[0°/45°/90°/-45°]_{6s}$ [27,36]. The most-used stacking sequences in actual production were $[0°/45°/90°/-45°]_s$, $[45°/0°/135°/90°/45°]_s$, etc.

The FRP laminate globally exhibits heterogeneous characteristic, anisotropy nature, and brittle behavior, which inevitably results in extremely poor machinability of the material. Structural components made of FRP laminates are mostly manufactured in near-net-shape in order to gain accurate dimensional tolerance and to ensure excellent assembly performance, especially in a hybrid composite configuration. The disparate natures of the fiber/matrix system, as well as its inherent heterogeneity, make the machining operation more difficult than conventional metal cutting. Drilling FRP phase in a hybrid composite configuration exhibits more challenging than the standard FRP drilling cases due to the coupled influences arising from the interface cutting and metal-phase cutting. Relevant discussion will be presented in the following sections of the paper.

2.2. Titanium alloy phase

The titanium alloy used in a hybrid stack configuration aims at providing high corrosion resistance and excellent fatigue properties of the assembly. The superior properties of titanium phase primarily have a close relation with the presence of its metallurgical matrix characteristics. In the viewpoint of the crystalline state, the titanium exists in two different phases referring to a low-temperature α phase (HCP) and a high-temperature β phase (BCC). The HCP structure of titanium affords a limited number of slip or shear planes while the BCC structure has more slip systems, thereby enabling more deformation locally transformed from HCP into BCC. Pure titanium typically undergoes an allotropic transformation probably at 882 °C, changing from the low-temperature close-packed hexagonal α phase to the high-temperature body-centered cubic β phase [7]. The allotropic transformation temperature is very sensitive to some certain added elements. For instance, the α stabilizers such as Al, O, N, Ga, and C elements produce an increase in the temperature while the β stabilizers such as Mo, V, Cu, Cr, Fe, Mn, Ni, ect., produce a decrease of the transformation temperature [37]. In contrast, some other neutral elements like Sn, Si, and Zr have gentle influences on the transformation temperature.

Typically, the Ti alloy can be categorized into four basic groups according to its main metallurgical characteristics: *(i)* commercially pure alloy, *(ii)* α and near α alloy, *(iii)* α-β alloy, and *(iv)* β alloy [7,37]. With regard to its machinability, the titanium alloy is still regarded as an extremely difficult-to-cut material in current manufacturing community due to its inherent properties like low thermal conductivity, low modulus of elasticity, high chemical affinity to tool materials, etc. Special issues may arise from the high force/temperature generation, rapid tool wear and poor surface integrity. Moreover, the Ti-drilling operation exerted in a hybrid composite configuration, obtains significant interrelated influences from the composite-phase drilling, making the cutting mechanisms more complicated than single Ti ally drilling cases. Detailed discussion will be presented later.

2.3. FRP/Ti assembly

The emergency of FRP/Ti assembly aims to overcome the individual limitations of each constituent involved and to obtain enhanced structural functions. The typical configurations of FRP/Ti stacks are CFRP/Ti6Al4V and GFRP/Ti6Al4V that are widely used in modern aerospace industry. The composite-metal system usually offers enhanced properties including high strength-to-weight ratio, higher specific strength, high corrosion resistance, etc., which makes it an ideal substitute for standard composite and single metal applications.

Drilling is indeed one of the most important and fundamental operations prior to the hybrid composite's application. However, due to the varying properties and poor machinability of the two stacked constituents, drilling FRP/Ti stack with acceptable hole quality poses the most challenging task in modern manufacturing industries. Severe hole damage, excessive interface consumption as well as rapid tool wear are the key problems encountered in drilling. Exploring the drilling behavior and improving the machinability of hybrid FRP/Ti stack play a crucial role in high efficiency-precision machining of the material. To this aim, great motivations have been exploited in order to address deeply the topics, and a large amount of scientific work has been undertaken within the past few decades. Table 1 summarizes the key experimental studies that have been performed in the open literature concerning FRP/Ti drilling [1,2,9,38–53].

3. Drilling force characterization

Force generation represents the key cutting characteristics activated in FRP/Ti drilling, which signifies the mechanical energy consumption of multi-tool–work interactions governing the chip removal process. In drilling operation, the force generation is usually decomposed into two components, i.e., the thrust-force component and torque component, which denotes the tribological behaviors between tool–chip interaction and tool–machined surface interaction, respectively. Severe force fluctuations in both thrust and torque components are often encountered when drilling hybrid FRP/Ti composite. The force-magnitude discrepancy mainly arises from the fiber orientation's effects on the FRP-phase drilling, the variable chip separation mode in interface drilling and the serrated chip formation in Ti-phase drilling. The changeable chip formation modes occurring on tool rake face would be the key factor significantly affecting the torque-force component in the stack drilling. The thrust force component, however, signifies the interactions between tool flank face and the machined hole wall surface. In addition, the disparate properties arising from the composite-metal phases also cause the drilling-force signal to exhibit certain stage characteristics. Fig. 2 shows the thrust force and torque signals varied with cutting depth when drilling FRP (Gr/Bi)/Ti stack by using standard HSS drill under the fixed cutting conditions of n = 660 rpm and f = 0.2 mm/rev [1]. It is observed that three major regions referring to the FRP, interface and Ti drilling zones in thrust and torque profiles are noticeable. Furthermore, the entire hybrid FRP/Ti drilling action can also be distinguished by seven minor regions (regions 1–7).

- Region 1 defines the period when the chisel edge firstly penetrates the FRP phase. Both the thrust and torque force components increase gradually from zero.
- Region 2 represents that the cutting lips gradually engage in the FRP-phase drilling. The cutting-force signals increase gradually with the tool advancement.
- Region 3 signifies the period of full engagement of the drill lips through the FRP-phase drilling. The thrust force and torque nearly keep constant in this region drilling.
- Region 4 denotes the period of drill bit involved in the FRP/Ti interface drilling. The tool–work interaction transfers from the absolute tool–FRP interaction, gradually to multi-tool–work interaction and finally to absolute tool–Ti interaction, resulting in the significant increase of the drilling forces.
- Region 5 indicates that the cutting lips have gradually cut into the Ti phase, and continuous force elevation has been obtained.

Table 1
Experimental researches concerning hybrid FRP/Ti drilling in the open literature [1,2,9,38–53].

Reference	Hybrid composite configuration	Drill bit details	Cutting conditions	Key topics addressed
Ramulu et al. [1]	FRP (Gr/Bi)/Ti6Al4V FRP: IM-6 graphite bismaleimide composite $\theta = [45°/90°/-45°/0°/-45°/0°/45°/0°/-45°/90°/-45°/0°/45°/0°/45°/90°/-45°/90°/90°]_s$ $T = 7.62/3.1$ mm	HSS, HSS-Co, carbide twist drills	$n = 325{,}660{,}1115{,}1750{,}2750$ rpm $f = 0.03{,}0.08{,}0.13{,}0.12{,}0.25$ mm/rev	Drilling forces, Hole production, Tool wear, Hole damage, Surface topography
Brinksmeier and Janssen [2]	$AlCuMg_2$/CFRP/Ti6Al4V $\theta = [45°/90°/0°/45°]_s$ $T = 10/10/10$ mm	Uncoated twist drill, Step drills (uncoated, TiB_2, diamond) $D = 16$ mm, $\phi = 130°$ $\psi = 30°$	$v_c = 10$, 20 m/min $f = 0.15$ mm Cutting environment: dry and oil mist conditions	Workpiece quality, Tool wear
Park et al. [9]	CFRP/Ti6Al4V CFRP: quasi-isotropic graphite/epoxy laminate $T = 7.54/6.73$ mm	WC twist drills $D = 9.525$ mm $\phi = 135°$ $\psi = 28°$	$n = 2000$, 6000 rpm (CFRP) $n = 800$, 400 rpm (Ti) $f = 0.0762$ (CFRP),0.0508 mm/rev (Ti) Cutting environment: dry and wet	Drilling forces, Tool wear, Hole quality
Park et al. [46]	CFRP/Ti6Al4V CFRP: multidirectional graphite epoxy composites $T = 7.54/6.73$ mm	WC, PCD drills $D = 9.525$ mm $\phi = 135°$ $\psi = 28°$	$n = 2000$, 6000 rpm (CFRP); 300, 400, 800 rpm (Ti) $f = 0.0762$ mm/rev (CFRP); 0.0508 mm/rev (Ti) Cutting environment: mist	Drilling forces, Tool wear
Isbilir and Ghassemieh [43]	CFRP/Ti6Al4V CFRP: T700-M21CFRP $\theta = [90°/-45°/0°/45°]_{5s}$ $T = 20/20$ mm	AlTiN twist drills $D = 8$ mm $\phi = 140°$ $\psi = 45°$	$n = 1400$ rpm (Ti) and 4500 rpm (CFRP) $f = 119$ mm/min (CFRP) and 457 mm/min (Ti)	Drilling forces, Delamination, Burrs, Surface roughness, Tool wear
Kim and Ramulu [44]	FRP (Gr/Bi)/Ti6Al4V FRP: IM-6 graphite bismaleimide composite $\theta = [45°/90°/-45°/0°/-45°/0°/45°/0°/-45°/90°/-45°/0°/45°/0°45°/90°/-45°/90°/90°]_s$ $T = 7.62/3.1$ mm	HSS-Co, split-Point, carbide drills	$n = 660{,}1115{,}1750$ rpm $f = 0.08{,}0.13{,}0.20{,}0.25$ mm/rev	Drilling process optimization, Hole quality, tool wear
Brinksmeier et al. [39]	$AlCuMg_2$/CFRP/Ti6Al4V CFRP: multilayer of unidirectional prepregs $T = 10/10/10$ mm	Twist drill, step drill $D = 16$ mm	$v_c = 40$ m/min $v_f = 5$ mm/min Cutting environment: minimum quantity lubrication (MQL)	Thermal and mechanical loads, Surface microstructure and damage
Shyha et al. [50]	Ti6Al4V/CFRP/Al-7050 $\theta = [45°/0°/135°/90°/45°/0°]_s$ $T = 10/10/10$ mm	Uncoated, CVD diamond-coated, C7-coated drills $D = 6.35$ mm $\phi = 130°$ $\psi = 30°$	20 m/min $\leqslant v_c \leqslant$ 120 m/min $f = 0.05{,}0.10{,}0.15$ mm/rev Cutting environment: wet, spray mist condition	Hole size, Hole surface roughness, Hole edge quality, Microhardness of metal, Chip formation
Ghassemieh [42]	CFRP/Ti6Al4V CFRP: M21E CFRP	C7-coated carbide drills $D = 6$ mm	$n = 1400$ and 4500 rpm $f = 119$ and 457 mm/min	Drilling forces, Tool wear, Surface roughness
Beal et al. [38]	CFRP/Ti6Al4V CFRP: quasi-isotropic graphite/epoxy laminate $T = 7.54/6.73$ mm	WC drills $D = 9.525$ mm $\phi = 135°$ $\psi = 28°$	$n = 400$, 800 rpm (Ti) $n = 2000$, 6000 rpm (CFRP) $f = 0.0508$ mm/rev (Ti) and 0.0762 mm/rev (CFRP) Cutting environment: wet lubrication condition	Drilling forces, Tool wear, Hole quality, Surface roughness
Park et al. [47]	CFRP/Ti6Al4V CFRP: quasi-isotropic graphite/epoxy laminate $T = 7.54/6.73$ mm	WC, BAM-coated drills	$n = 2000$, 6000 rpm (CFRP); 400, 800 rpm (Ti) $f = 0.051$ mm/rev	Tool wear, Tool performance
Fujiwara et al. [41]	CFRP/Ti6Al4V CFRP: composed of 1 ply GFRP and 10 ply CFRP $T = 3/9.5$ mm and 3/10.5 mm	TiAlN, TiSiN and TiAlCr/TiSi-coated drills $D = 6$ mm	$v_c = 18.8$ m/min $f = 0.2$ mm/rev Cutting environment: dry and mist-water cooling	Drilling forces, Tool wear, Hole quality
Tashiro et al. [51]	CFRP/Ti6Al4V CFRP: composed of 1 ply GFRP and 10 ply CFRP $T = 3/9.5$ mm	TiAlN, TiAlCr/TiSi coated drills $D = 6$ mm	$v_c = 9.4$, 18.8 m/min $f = 0.1$, 0.2 mm/rev Cutting environment: dry and water-mist-cooling	Cutting forces, Tool wear, Hole quality, Cutting environment comparison

Table 1 (*continued*)

Reference	Hybrid composite configuration	Drill bit details	Cutting conditions	Key topics addressed
SenthilKumar et al. [49]	CFRP/Ti6Al4V	Solid WC twist drills (with different tool point angles) $\phi = 130°$ $\psi = 30°$	$n = 612$ and 1826 rpm $f = 0.05$ mm/rev	Tool wear, Chip formation, Effects of drill point angle on tool wear
Poutord et al. [48]	CFRP/Ti6Al4V $T = 20.7/25.5$ mm	K20 uncoated drill $D = 12$ mm $\phi = 140°$ $\psi = 30°$	$n = 2652$ rpm (CFRP); 265 rpm (Ti) $f = 0.05$ mm/rev (CFRP); 0.2 mm/rev (Ti)	Drilling forces, Tool wear
Kuo et al. [45]	Ti6Al4V/CFRP/Al-7050 $\theta = [45°/0°/135°/90°/45°/0°]_{3s}$ $T = 10/10/10$ mm	DLC diamond drill, CVD diamond drill $D = 6.38$ mm $\phi = 140°$ $\psi = 30°$	$v_c = 30$ m/min (Ti); $v_c = 120$ m/min (CFRP, Al) $f = 0.08$, 0.15 mm/rev	Thrust force, Torque, Tool wear, Hole accuracy, Burr formation
Carvajal et al. [40]	CFRP/Ti; CFRP/Al; CFRP/CFRP	Not specified	Variable cutting conditions including drilling machine, nature of materials, feed rate, spindle speed, etc.	Effects of different input factors on hole diameter
Wang et al. [52]	CFRP/Ti6Al4V, Ti6Al4V, CFRP $\theta = [(0°/45°/90°/-45°)_4\ (0°/90°/0°/90°)]_s$ $T = 7.54/6.73$ mm	Uncoated, AlTiN, nanocomposite coated drills $D = 9.525$ mm $\phi = 135°$ $\psi = 25°$	$n = 6000$ rpm, $f = 0.0762$ mm/rev (CFRP, CFRP/Ti); $n = 500$ rpm, $f = 0.0508$ mm/rev (Ti, CFRP/Ti)	Drilling forces, Tool wear mechanisms in CFRP-only, Ti-only and CFRP/Ti drilling
Matsumura and Tamura [53]	CFRP/Ti $T = 4/4$ mm	TiAlN coated twist drill $D = 6$ mm $\phi = 120°$ $\psi = 20°$	$v_c = 10$, 25 m/min, $f = 0.05$, 0.1 mm/rev	Drilling-force models Predicted forces Measured forces

The maximum thrust force is achieved at the end of this region drilling.

- Region 6 demonstrates that the cutting lips have totally cut into the Ti phase.
- Region 7 entails the period that the chisel edges have gradually penetrated out of the Ti phase. The thrust force component is found to decrease gradually to zero. However, the torque component above zero is expected at the end of the process due to tool friction, depending on the elastic springback effect of the composite material.

Moreover, the force generation in FRP/Ti drilling exhibits strong sensitivity to the input variables. Special variables commonly addressed are drilling parameters (spindle speed and feed rate), drilled hole number (tool wear), etc. Ramulu et al. [1] studied the influence of drilling parameters on the force generation when drilling FRP (Gr/Bi)/Ti stacks. Results presented in Fig. 3(a) and Fig. 3(c) indicated that the feed rate had significant effects on the thrust force magnitudes in such manner that a slight increase of feed rate gave rise to the dramatically elevated thrust force, irrespective of the used tool materials. The reason can be attributed to the increased cutting resistance when feed rate was elevated. In contrast, the relation between spindle speed and thrust force was obscure. And more precisely, the spindle speed was observed to have minor effects on the thrust force generation in all regions except region 7 when using HSS and carbide drills as depicted in Fig. 3(b) and Fig. 3(d), respectively. In other literature [42,43], the spindle speed was confirmed to exhibit positive impacts on the drilling forces for FRP-phase drilling while to have negative impacts on the drilling forces for Ti-phase drilling. The phenomena can be attributed to the hardening or softening effects of the increased high temperature on the work materials caused by the elevated spindle speed, respectively.

In most open literature, drilled hole number (tool wear) was identified as another key factor significantly influencing the drilling force generation. Fig. 4 shows the experimental results gained by Park et al. [46] when drilling CFRP/Ti6Al4V stacks with WC and PCD drills. It is noticeable that both the thrust force and torque produced in CFRP-phase drilling and Ti-phase drilling exhibit linearly proportional to the drilled hole number, regardless of the used tool materials. The phenomenon can be explained by the fact that when a large number of holes have been drilled, the tool will suffer excessive and expanded tool wear. As a result, the tool undergoes high tool-work friction coefficient when drilling further uncut chip material, resulting in high cutting energy consumption and subsequent high-force generation. The identical findings were also confirmed by Beal et al. [38], Fujiwara et al. [41], Tashiro et al. [51] and Wang et al. [52].

4. Cutting mechanisms controlling FRP/Ti drilling

Drilling hybrid FRP/Ti composite exhibits quite different from drilling standard composites and single metal alloys due to the multi-tool–work interaction domains. The disparate natures of each constituent make the chip separation mode more coupled and interrelated governing the bi-material interface consumption (BIC). The interrelated cutting mechanisms play a pivotal role in affecting the machining responses and induced surface quality. Revealing the mechanisms controlling FRP/Ti drilling can provide a beneficial guide for the cutting-parameter optimization, hole-quality controlling and drill-bit selection.

In FRP/Ti drilling, two different cutting-sequence strategies, i.e., cutting from Ti → FRP and cutting from FRP → Ti, exist from the aspect of tool-entry and tool-exit throughout the material removal process. From the viewpoint of vertical drilling configuration, the reasonable cutting sequence would rest the FRP laminate on top

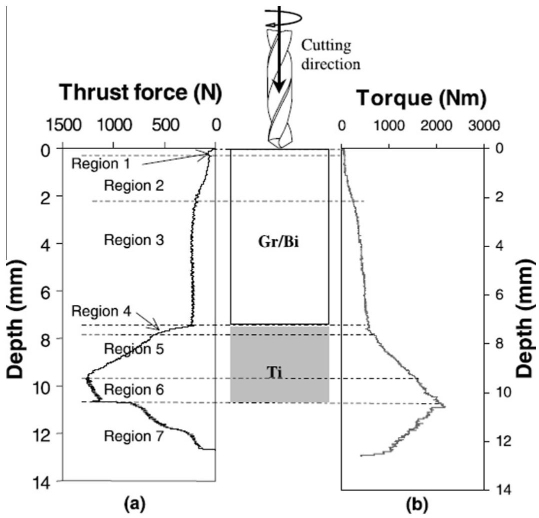


Fig. 2. Drilling force signals *versus* cutting depth when drilling hybrid FRP/Ti composite by using standard HSS drill. (Material: Gr/Bi FRP/Ti6Al4V, $\theta = [45°/90°/-45°/0°/-45°/0°/45°/0°/-45°/90°/-45°/0°/45°/0°/45°/90°/-45°/90°/90°]_s$, cutting parameters: n = 660 rpm and f = 0.2 mm/rev) [1].

of the Ti alloy and cut from the FRP phase first as illustrated schematically in Fig. 5 [11,46]. This is because in such cutting sequence the Ti alloy can act the role of supporting plate in preventing laminate inflection and limiting the workpiece dynamics during the drilling operation. As a result, it can lead to the low-extent delamination occurrence and improved tool life. The beneficial roles of FRP → Ti drilling sequence were also proven by several relevant researches [1,43,46]. Fig. 6 presents a comparison of the exit CFRP surface damage generated in drilling standard CFRP laminate without Ti phase and in drilling hybrid CFRP/Ti stack [43]. It was apparent that the CFRP → Ti drilling sequence promoted less fiber pullout (probably near-net shape) than the standard CFRP drilling case. Therefore, following the proposed drilling sequence (FRP → Ti), the FRP/Ti drilling mechanisms are then discussed from FRP-phase drilling, to interface drilling and finally to Ti-phase drilling, respectively.

4.1. FRP-phase drilling: brittle fracture dominant mechanisms

In FRP-phase drilling, the cutting mechanisms differ significantly from conventional metal cutting cases due to the brittleness and heterogeneity of the fiber/matrix system. The mechanisms governing the FRP-phase drilling should be responsible for the specific chip formation mode and chip morphology type.

When drilling FRP phase, material removal occurs through a series of successive fracture aided by diverse nature and uneven load shearing between the matrix and fibers. The chip formation mechanisms of FRP-phase cutting can be basically divided into three categories: *(i)* layered peeling fracture mechanism when the direction of cutting speed is consistent with the fiber direction; *(ii)* extrusion shear fracture mechanism when the direction of cutting speed is in an acute angle with the fiber direction; and *(iii)* bending shear fracture mechanism when the direction of cutting speed is in an obtuse angle with the fiber direction as shown in Fig. 7 [54]. Since brittle fracture operates as the predominant chip separation mode, the resected FRP chips are often produced in the form of "powdery" dust. However, the chip type generated in drilling greatly depends on the properties and volume fraction of the reinforcing fibers. In some cases, the "continuous" chip formation

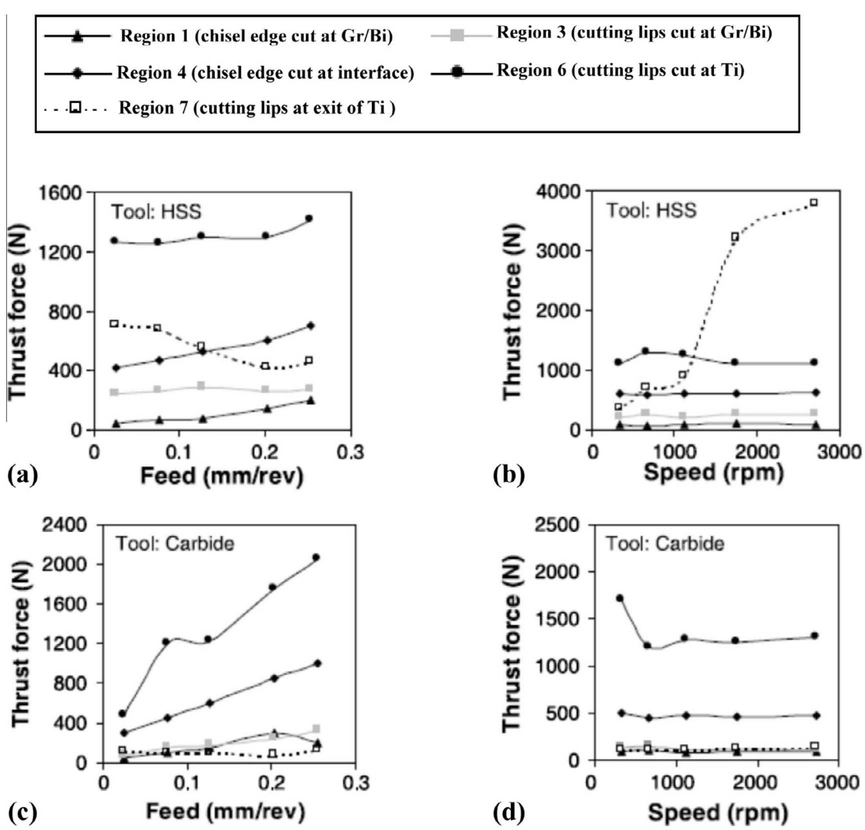


Fig. 3. Thrust force *versus* feed rate and spindle speed when drilling hybrid FRP/Ti composite: (a) n = 660 rpm – HSS drill, (b) f = 0.0732 mm/rev – HSS drill, (c) n = 660 rpm – carbide drill, (d) f = 0.0732 mm/rev – carbide drill. (Material: Gr/Bi FRP/Ti6Al4V, $\theta = [45°/90°/-45°/0°/-45°/0°/45°/0°/-45°/90°/-45°/0°/45°/0°/45°/90°/-45°/90°/90°]_s$, T = 7.62/3.1 mm) [1].

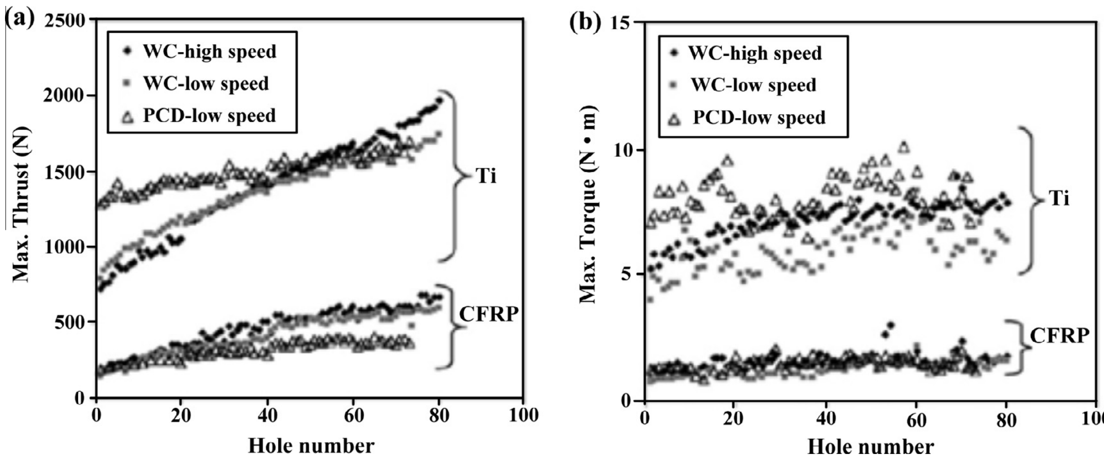


Fig. 4. Effects of the drilled hole number on (a) thrust force and (b) torque when drilling hybrid FRP/Ti composite by using WC and PCD drills. (Material: multidirectional graphite epoxy composites/Ti6Al4V, $T = 7.54/6.73$ mm; cutting tools: WC and PCD with $\phi = 135°$, $\psi = 28°$; cutting parameters: WC – high speed: n (CFRP) = 6000 rpm, n (Ti) = 800 rpm; WC-low speed: n (CFRP) = 2000 rpm, n (Ti) = 400 rpm; PCD-low speed: n (CFRP) = 2000 rpm, n (Ti) = 300 rpm; f (CFRP) = 0.0762 mm/rev, n (Ti) = 0.0508 mm/rev; cutting environment: mist coolant) [46].

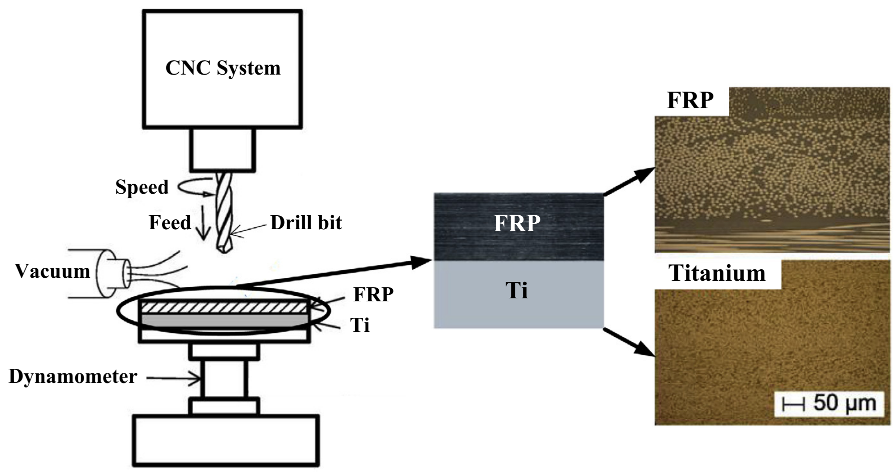


Fig. 5. Schematic illustration of the FRP → Ti cutting sequence used in vertical drilling of hybrid FRP/Ti composite [11,46].

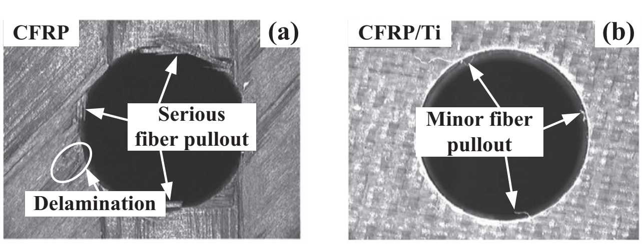


Fig. 6. CFRP surface damage at the exit side after drilling the 1st hole: (a) drilling of standard CFRP laminate after making the 1st hole and (b) drilling of hybrid CFRP/Ti composite (CFRP → Ti drilling sequence). (Material: CFRP (T700-M21, $\theta = [90°/-45°/0°/45°]_{5s}$, $T = 20$ mm)/Ti6Al4V (T = 20 mm); cutting tool: AlTiN twist drill; cutting parameters: $n = 4500$ rpm, $f = 457$ mm/min) [43].

as like the metal cutting can also be generated. The experimental findings obtained by Hocheng and Puw [55] indicated that when drilling carbon/epoxy the main chip type was absolutely "discontinues" form while for carbon/acrylonitrile butadiene styrene (ABS) drilling, the predominant chip type would be "continuous" one. The activated mechanisms controlling the chip characteristics could be explained by the fact that the material removal of the former was governed by brittle fracture while the latter was ruled by predominant plastic deformation due to the ABS's capacity of large elongation under cutting loads. In addition, when increasing fiber volume fraction, the majority of the composite materials are removed by a series of fracture due to the non-uniform plastic deformation and thus promoted the formation of "discontinuous" chip shape. Moreover, the chip type is also influenced by input cutting parameters like feed rate. Results gained by Kim et al. [56] showed that when low-feed drilling ($f = 0.02$ mm/rev) of PEEK thermoplastic composites, the produced chips were typically "continuous" and curling for a wide range of speeds due to the high overall toughness of the thermoplastic matrix. In contrast, when higher feed rate was employed ($f = 0.25$ mm/rev), the generated chips were basically "discontinuous". Anyway, the mechanisms controlling the chip separation can be identified as the key contributor to the resected chip shape. The chip-separation mechanism dominating the FRP-phase drilling, however, is critically dependent on tool rake angle (γ), and fiber cutting angle (the angle between the fiber direction and cutting-speed direction). However, these factors are not reviewed here individually since the key objective of the paper aims to survey the mechanism issues focused on hybrid composite drilling. Readers are recommended to refer to the mentioned literature [23,24,27,57–63]. Also, it should be stressed that in drilling, the changeable fiber breaking type *versus*

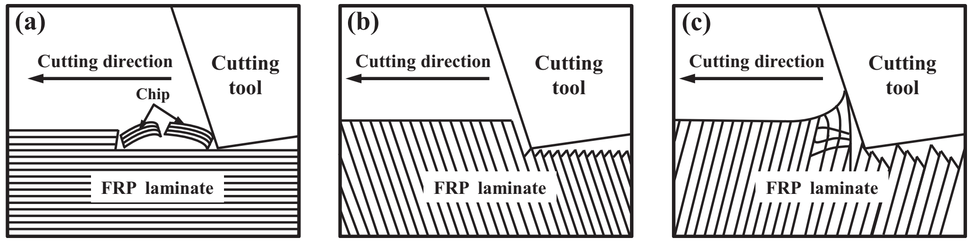


Fig. 7. Scheme of the chip formation mechanisms in FRP laminate cutting: (a) layered peeling fracture; (b) extrusion shear fracture and (c) bending shear fracture [54].

θ, on one hand, is a key contributor to the severe hole-wall damage formation like inter-ply delamination, fiber pullout, matrix degradation, etc. On another hand, it makes the distribution of some local defects, e.g., fiber pullout, delamination, spalling, etc., exhibit regional symmetrical characteristic. Such findings were also confirmed by some pertinent research work [61,64,65].

4.2. Interface drilling: interrelated and mixed cutting mechanisms

In this subsection, a new term "interface" was introduced to signify the most important zone, i.e., the "FRP-to-Ti" contact boundary, for the illustrations of the hybrid composite drilling process. The interface region is usually a physically intermediate transition zone that really exists in the bi-material machining process. During interface drilling, the area commonly suffers changeable chip-separation modes and experiences severe mechanical/physical phenomena transition when the tool drilling from FRP phase to Ti phase and vice versa. In such circumstance, the interface drilling should represent the most challenging operation as compared to the FRP-phase cutting and Ti-phase cutting, when drilling hybrid FRP/Ti composite. In FRP/Ti drilling, the bi-material interface machining commonly involves multiple aspects of mechanical/physical consumption governing the material removal process. The interrelated BIC makes the region more vulnerable to severe damage formation and defect generation. As the drill bit penetrates into the FRP/Ti interface (as shown in Fig. 8), discontinuous tool–work interaction including tool–FRP coupling and tool–Ti coupling takes place and makes the tool involve in a multi-tool–work interaction machining. The non-compliance among the tool–work interfaces inevitably gives rise to a particularly harsh cutting condition, and more interrelated cutting behavior governing the drilling operation. The cutting-edge segments as depicted in Fig. 8 will then experience a mixed material removal process of fiber brittle fracture and metal plastic deformation simultaneously throughout the multi-tool–work interaction time.

The multi-tool–work interaction time (t_m) governing the interface drilling, as depicted in Fig. 8, is critically dependent on the used drill diameter (D), drill point angle (ϕ), spindle speed (n) and feed rate (f), and can be expressed as follows:

$$t_m = \frac{D}{2nf}\cot\frac{\phi}{2} \quad (1)$$

During the interface drilling period, the main cutting edges, on one hand, undergo disparate thermal/mechanical responses arising from the multiple tool–work interfaces. On another hand, they experience an dynamic contact transition during the material removal process, i.e., shifting from absolute tool–FRP interaction to multi-tool–work interaction and finally to absolute tool–Ti interaction. As a result, the cutter will suffer intense force fluctuation and load vibration, and hence will result in the instability of the tool-work system during the stack drilling. These phenomena can be identified as a main trigger to the hole damage formation concerning the FRP/Ti interface. In addition, since the tool–FRP coupling and tool–Ti coupling exhibit disparate tribological behaviors, the drill bit in such condition will suffer mixed wear patterns during the interface cutting. The combined wear modes will significantly accelerate the tool wear rate and greatly shorten the tool life.

To alleviate the detrimental effects arising from the interface drilling, reducing the multi-tool–work interaction time would be a direct solution. As shown in Eq. (1), it can be inferred in theory that reducing drill diameter (D), increasing point angle (ϕ), spindle speed (n) or feed rate (f) can lead to the reduction of interface cutting time, and hence can promote desirable drilling results. In general, the interface drilling can be regarded as the most difficult cutting stage as compared to the FRP-phase drilling and Ti-phase drilling. However, to the authors' best knowledge, the underlying mechanical/physical behavior governing the interface drilling and also the parametric effects on BIC are still not fully understood. Relevant in-depth researches concerning the issues are rarely

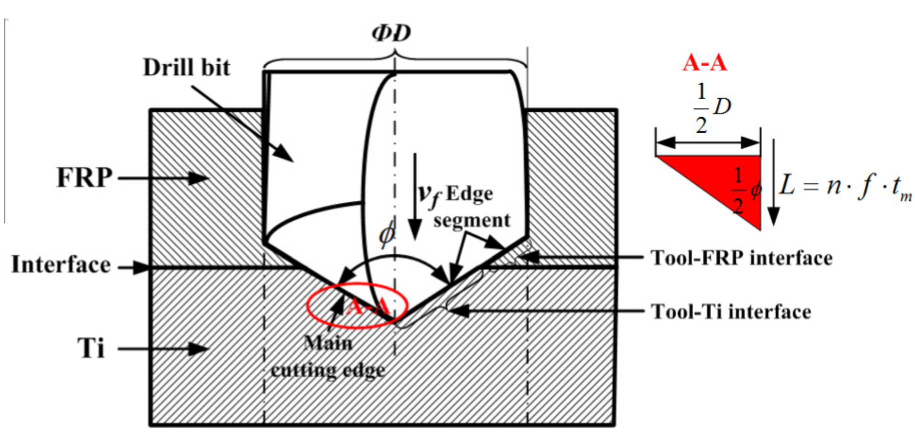


Fig. 8. Scheme of the drill bit involved in the FRP/Ti interface drilling.

found. The lack of experimental studies on the mentioned topics can be attributed to the difficulty in inspecting the multiple and sophisticated tool–work interaction in actual drilling cases. In the future, great efforts should be made to address deeply the issues.

4.3. Ti-phase drilling: plastic-defamation dominant mechanisms

When the drill edges thoroughly cut into the Ti phase, the multi-tool–work interaction absolutely shifts into the tool–Ti interaction. The elastic–plastic deformation then dominates the tool-Ti interaction area. The shearing actions from the thermal/mechanical effects generate "continuous" chips that flow on the tool rake face. Under such fixed condition, the drilling process is assumed to reach a steady state for which the cutting force, drilling temperature, and surface integrity could be predicted with an acceptable accuracy. However, since the Ti phase has poor thermal conductivity and strong chemical affinity to the used tool materials, the drilling action may cause serious hole damage and catastrophic tool failure [20,46]. On one hand, the smaller contact area between tool–chip interfaces in Ti drilling often results in stress concentration at the tool edge where the maximum cutting stresses are reached. In addition, the poor thermal conductivity of Ti alloy often results in inefficient heat dissipation and causes intense heat accumulation on tool substrate, which will lead to the severe thermal damage of the tool cutting surface. On another hand, the hot and continuous chips produced in Ti drilling also considerably impair the machined FRP hole and deteriorate the hole quality during their evacuation from the bottom layer.

The detrimental chip evacuation always causes catastrophic abrasion and erosion, and consequently high hole diameter tolerance in the FRP phase. Such results observed by Brinksmeier and Janssen [2] showed that the scratching effect of Ti chips on the machined CFRP hole could cause a high-depth erosion of approximately 300 μm when using conventional twist drill in multi-layer $AlCuMg_2$/CFRP/Ti6Al4V stack drilling. To alleviate the chip-evacuation effects, some researchers [1,44] asserted that it was not suggested to employ cutting parameters consisting of low spindle speed and low feed rate in hybrid composite stack drilling since these low parametric values favored the formation of "continuous" Ti chips, which would result in a great extent of subsurface damage in the polymeric holes.

Table 2
Commonly-induced hole damage types when drilling hybrid FRP/Ti composite.

Phase type	Drilling-induced damage
FRP phase	Matrix cratering, delamination, fuzzing, micro crack, fiber/matrix debonding, spalling, fiber pullout, fiber breaking, resin loss, surface cavities, thermal alteration, etc.
FRP/Ti interface	Discoloration ring, damage ring, delamination, etc.
Ti phase	Hole size error, roundness error, position error, surface drag, burr, cracking, feed marks, tearing surface, debris of microchips, surface plucking, deformed grains, surface cavities, etc.

5. Drilling-induced damage

Drilling-induced damage is often characterized by the extent of geometric defects, thermal injuries and physical imperfections. For hybrid FRP/Ti drilling, the induced hole damage comprises both the composite defects (e.g., matrix cratering, inter-ply delamination, fiber pullout, thermal alteration, etc.) [66] and the metallic imperfections (e.g., hole size error, roundness error, position error, burrs, etc.). The composite-metallic damage usually results in the poor assembly tolerance and long-term performance deterioration of the machined structural components. A list of the commonly addressed hole damage in FRP/Ti drilling is summarized in Table 2. Fig. 9 [3,44] shows the schematic diagram of the drilling-induced hole damage distribution in FRP/Ti stack.

5.1. Hole damage produced in FRP phase

In FRP phase drilling, damage formation commonly occurs through a series process of matrix cracking, fiber fracture and inter-laminar delamination, etc. Due to the heterogeneity and anisotropy of the fiber/matrix system, severe hole damage is often promoted in drilling. Generally, the drilling-induced damage of the FRP phase can be classified into the following categories: geometric defects, temperature-related damage, delamination at drill-entry and drill-exit [67]. The tool geometry related damage is associated with the angle between the fiber orientation and the cutting edge. The temperature-induced damage including micro crack, resin loss, and matrix degradation is commonly produced by the thermal effects of drilling heat on the hole wall surface. In contrast, the damage due to delamination is usually a matter of greatest concern as it affects surface finish and work strength significantly

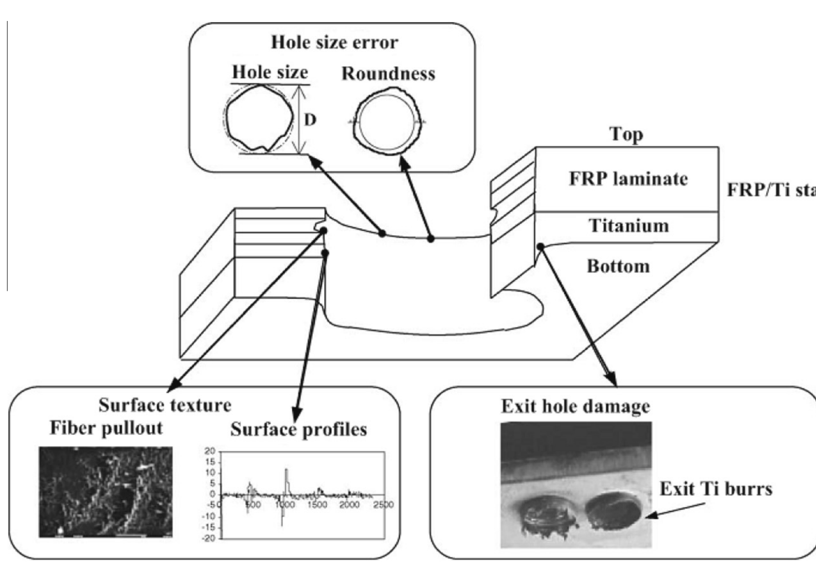


Fig. 9. Schematic diagram of the hole damage distribution in hybrid FRP/Ti drilling [3,44].

leading to a great deal of part rejections. The delamination depends on not only the fiber/matrix nature but also its adjacent properties [68,69]. Note that in standard FRP drilling, two mechanisms responsible for delamination occurrence may operate at both the entry and exit of the drilled hole periphery, which are well-known as “peel-up delamination” and “push-out delamination”, respectively. However, in hybrid FRP/Ti stack drilling, especially under FRP → Ti drilling sequence, the peel-up delamination may become a predominant mode while the push-out delamination exhibits less possibility to happen due to the beneficial effects of the bottom-supporting Ti phase on preventing the inflection and deformation of the upper composite laminate. Qi et al. [70] further revealed that the bottom-supporting metal thickness also has significant effects on the push-out delamination formation, especially when the metal thickness exceeds a so-called critical value (a specified thickness threshold for the free-delamination occurrence) no push-out delamination takes place. For peel-up delamination, as the drill bit cuts into the FRP phase, the drill cutting edges abrade the laminate. In such circumstance, a concentrated peeling force will be formed through the slope of the drill flutes and then separates the fiber plies from the uncut portions beneath the tool forming a delaminated zone around the hole entry periphery, as illustrated in Fig. 10.

Since the delamination belongs to an irreparable damage and an inter-ply failure, it is recognized as the most critical damage that severely impairs the performance of the machined components and accounts for probably 60 % of the part rejections in the aerospace industry [27,55,67,71–73]. In general, it is believed by many scholars [70,74–76] that there exists a critical thrust force (CTF) in composite drilling or composite/metal drilling, below which no delamination takes place. For detailed information about CTF, readers are recommended to refer to the mentioned literature [70,74–76]. In order to predict the CTF in hybrid composite drilling, Qi et al. [70] established the analytical models based on the linear elastic fracture mechanics, classical bending plate theory and classical lamination theory. In their proposed models, the CTF (P) responsible for the push-out delamination is simplified as a resultant force of a concentrated one (P_{ch}) at the chisel edge and a uniformly distributed one q at the cutting lips [77]. Both CTF models in two drilling sequences, i.e., drilling from metal → FRP and drilling from FRP → metal, were discussed in their research, which are illustrated in Fig. 11 and summarized in Table 3, respectively. The calculated results showed that when drilling from FRP → metal sequence, the CTF yielded a higher value than that operated from metal → FRP sequence. The phenomenon indicated that drilling sequence of FRP → metal would be more beneficial for minimizing delamination when drilling hybrid composite stacks. The predicted results showed consistent agreement with their experimental validation. However, the established models were restrained to solely predicting the CTF of conventional twist drill in drilling hybrid FRP/metal composite and ignored some internal factors like the effects of composite layup and plate shape on push-out delamination.

In addition, the delamination visualization and assessment in hybrid FRP/Ti drilling also pose a challenging task because of its internal-external nature. At present, the most used non-destruction methods for characterizing the size, shape, and location of delamination are optical microscopy, ultrasonic C-Scan, and X-ray computerized tomography [72,75,76,78–82]. For delamination extent, it is often evaluated by using one-dimensional delamination factor (F_d) [16,65,76] (signify the delamination evaluation based on the one-dimensional scale: diameter, the ratio of

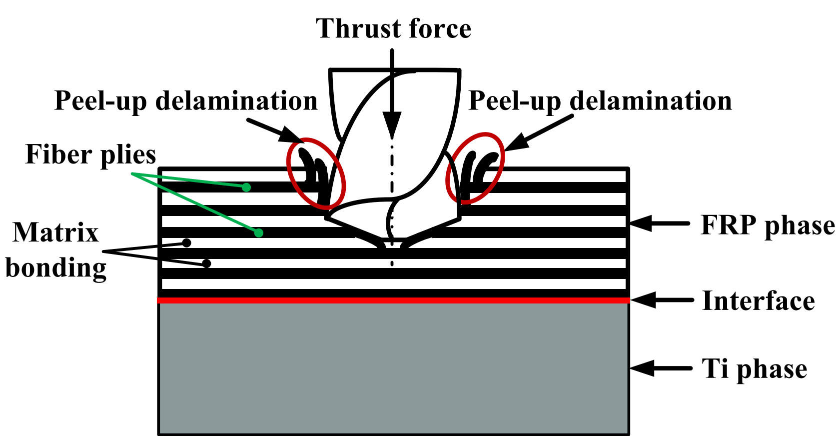


Fig. 10. Schematic illustration of the peel-up delamination occurred in hybrid FRP/Ti drilling (FRP → Ti drilling sequence).

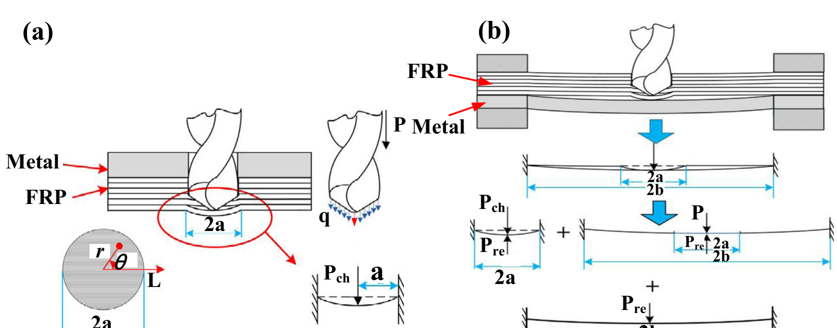


Fig. 11. Delamination analysis for different cutting-sequence strategies applied in hybrid FRP/metal drilling: (a) metal → FRP cutting sequence and (b) FRP → metal cutting sequence [70].

Table 3
Analytical models for predicting CTF under different cutting-sequence strategies when drilling hybrid FRP/metal composite [70].

Drilling sequence	Scheme of delamination	Analytical model of critical thrust force (CTF)
Metal → FRP cutting sequence	Fig. 11(a)	$CTF_I = P_I = \frac{2\pi}{\xi}\sqrt{G_{IC}(3D_{11} + 2D_{12} + 3D_{22} + 4D_{66})}$ $D_c = \frac{1}{3}(3D_{11} + 2D_{12} + 3D_{22} + 4D_{66})$
FRP → metal cutting sdequence	Fig. 11(b)	$CTF_{II} = P_{II} = \frac{2\pi}{\xi - K}\sqrt{G_{IC}(3D_{11} + 2D_{12} + 3D_{22} + 4D_{66})}$ $K = \frac{\frac{\xi a^2}{D} + \frac{2a^2 \ln\frac{a}{b} + (b^2 - a^2)}{D_c}}{\frac{9(1-v^2)b^2}{2Eh^3} + \frac{a^2}{b} + \frac{2a^2 \ln\frac{a}{b} + (b^2 - a^2)}{D_c}}$

Remarks: G_{IC} – the critical energy release rate in mode I; ξ-proportional coefficient; D_{11}, D_{12}, D_{22}, D_{66} – coefficients stand for the bending stiffness of the uncut FRP laminate; D_c – the equivalent bending stiffness coefficient of the FRP laminate; v – Poisson's ratio; E – elastic modulus; a, b, h – dimensional constants as seen in Fig. 11.

the maximum diameter (D_{max}) of the delamination area to the hole nominal diameter (D_{nom})), two-dimensional delamination factor (D_{RAT} or D_F) [17,83,84] (denote the delamination evaluation based on the two-dimensional scale: area) and adjusted delamination factor (F_{da}) [85] (signify the comprehensive consideration of both F_d and D_{RAT}) as summarized in Table 4. The main differences among the three criteria relay on fact that the one-dimensional delamination factor represents the simplest way to evaluate the delamination extent induced in real production while the two-dimensional and adjusted delamination factors can accurately assess the real extent of delamination damage since they minimize the influences of a few peeled-up or pushed-down fibers on the delamination measurement.

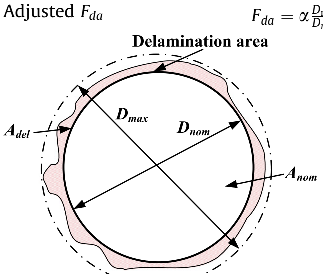
5.2. Interface damage: the weakest boundary region

In FRP/Ti drilling, the interface linking composite and metal boundaries would be the weakest region vulnerable to severe damage formation due to the unstable cutting process resulting from the non-compliance tool–work interactions. When the cutting tool reaches the interface region, the tool tips and cutting edges suffer severe shocks and vibrations due to the changeable chip separation modes from tool–FRP interaction to tool–Ti interaction and vice versa. Such physical phenomenon makes the drilling operation much easier to promote damage formation. Generally, the interface damage was reported in the form of discoloration ring, damage ring, fiber pullout and delamination as shown in Fig. 12 [1]. The mentioned interface damage was often irreparable and fatal, which would promote crack initiation and fatigue fracture during the stack's assembly process.

Concerning the interface damage formation, several scholars [1,9] have revealed that the cutting heat and chip evacuation are the pivotal factors contributing to the damage initiation and propagation. Specific reason can be attributed to the unique physical properties of the Ti phase. Since the Ti alloy is characterized by poor thermal conductivity ($\lambda_s \approx 7–7.9\ \mathrm{W\ m^{-1}{}^{\circ}C^{-1}}$), the cutting

Table 4
Commonly-used delamination factors for damage evaluation when drilling FRP laminates [16,17,65,76,83–85].

Type of delamination factor	Equation expression	Remarks	Reference
One-dimensional F_d	$F_d = \frac{D_{\max}}{D_{nom}}$	D_{max} – maximum diameter of the delamination area; D_{nom} – nominal diameter of the drilled hole	Chen [16], Xu et al. [65], Tsao and Hocheng [76]
Two-dimensional D_{RAT} or D_F	$D_{RAT} = \frac{A_{del}}{A_{nom}}$ $D_F = \left\lvert\frac{A_{del} - A_{nom}}{A_{nom}}\right\rvert \times 100\%$	A_{del} – delamination area; A_{nom} – nominal area of the drilled hole	Faraz et al. [17], Davim and Reis [83], Mehta et al. [84]
Adjusted F_{da}	$F_{da} = \alpha\frac{D_{\max}}{D_{nom}} + \beta\frac{A_{del}}{A_{nom}}$	α, β – the used weights in F_{da}	Davim et al. [85]



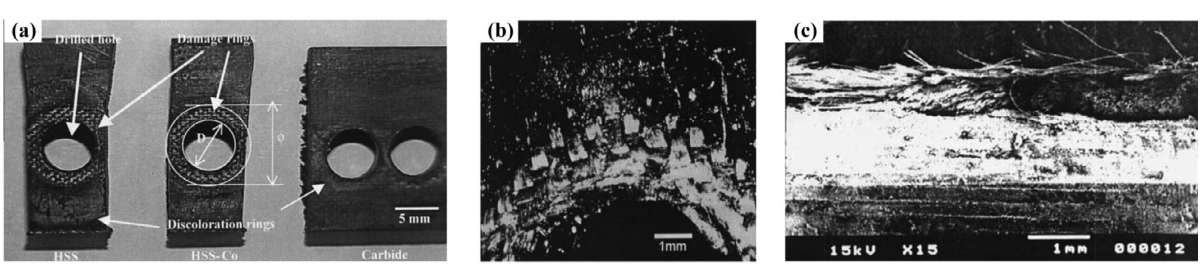


Fig. 12. (a) Damage region at the composite/Ti interface, (b) the top view of the damage region, and (c) the side view of the damage region of (b). (Material: Gr/Bi FRP/Ti6Al4V, θ = [45°/90°/−45°/0°/−45°/0°/45°/0°/−45°/90°/−45°/0°/45°/0°/45°/90°/−45°/90°/90°]$_s$, T = 7.62/3.1 mm; (a): cutting tools: HSS, HSS-Co and carbide drills, cutting parameters: n = 1750 rpm, f = 0.08 mm/rev; (b) and (c): cutting tool: HSS-Co drill, cutting parameters: n = 2720 rpm, f = 0.08 mm/rev) [1].

heat generation around the interface can't be dissipated effectively, which, in turn, induces a local heat concentration at the bi-material interface. The accumulated cutting heat will cause thermal softening and degradation of the FRP/Ti interface. Besides, the produced Ti chips also result in severe scratches and intense abrasions on the bi-material interface, leading to the force-induced delamination. In addition, Ramulu et al. [1] pointed out that the drilled hole number (tool wear) and feed rate also influenced the interface damage. For instance, when lower feed rate was used, larger interface damage was generated due to the longer tool-work engagement resulting in more Ti heat generation accumulated on the interface region.

5.3. Hole damage produced in Ti phase

When the tool edges attack the Ti phase, the previous brittle fracture changes into elastic–plastic shearing, thus the generated surface quality tends to be improved a bit as compared to the FRP-phase drilling. However, the most significant problem in hybrid composite drilling always occurs in this phase due to the poor thermal conductivity of the Ti alloy that leads to the localized heat generation concentrated at the tool–chip interface. The thermal congestion inevitably results in high cutting temperature governing the tool active zones, exacerbating the interface damage, burr defect, heat-induced delamination and surface roughness. The main forms of surface defects reported in literature [21,86–88] are surface drag, burrs, cracking, feed marks, tearing surface, debris of microchips, surface plucking, deformed grains, surface cavities, etc. These mentioned defects usually have a close relation with the thermal/mechanical influences arising from the drilling action and depend considerably on the used cutting conditions. For the purpose of FRP/Ti assembly, the burr defect produced in Ti phase may be a key problem compared to other surface damage since it usually leads to further disassembly, deburring and re-assembly of the stack. The burr formation induced in drilling is primarily dependent on the tool geometry and tool/work orientation (that is, whether the hole axis is orthogonal or not to the plane of the exit surface of the hole) [89].

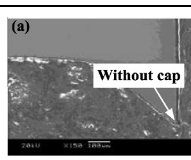
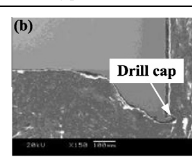
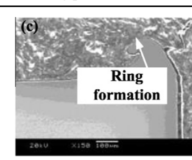
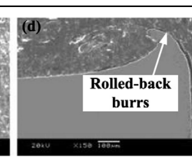
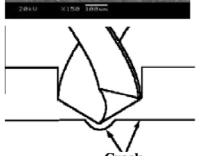
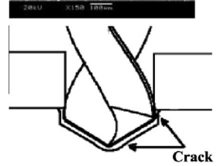
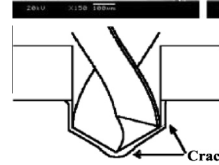
Normally, the drilling-induced Ti burrs are often classified into three types, namely type A, type B and type C according to the location of the initiated crack, as illustrated in Table 5. It was defined by authors Ko and Lee [90], Ko et al. [91] and Dornfeld et al. [86] that *(i)* burr type A was formed with a very small size or a negative shape due to the brittleness of the material; *(ii)* burr type B was produced as a result of some degree of plastic deformation and was characterized by a uniform drill cap; *(iii)* burr type C typically had a severe rolled-back shape and large "ring formation" due to the crack initiated from the drill point of the cutting edges.

The results obtained by Shyha et al. [50] when drilling Ti6Al4V/CFRP/Al-7050 stacks showed that in general, the Ti burrs without and with caps (Type A and Type B) were produced at the hole exit side, while rolled-back burrs (Type C) were pronounced at the hole entry side, as illustrated in Table 5. The induced exit burrs usually cause serious problem for further assembly of the stack. To minimize or even prevent the burr formation, it is critical to choose the proper cutting parameters, superior tool material as well as the effective use of cutting environment for the drilling applications. Kim and Ramulu [3] studied the effects of cutting parameters on the exit burr height by using carbide tools in drilling autoclaved and induction heated hybrid composite stacks (PIXA-M thermoplastic composite/Ti). It was found that the exit burrs showed high dependence on the spindle speed and feed rate. When low spindle speed and high feed rate were employed, lower burr height could be achieved, as shown in Fig. 13(a) and Fig. 13(b). Besides, some other researchers [50,92] pointed out that the use of fresh tool and superior tool material (e.g., polycrystalline diamond) could also benefit the burr height minimization when drilling hybrid composite stack. For cutting environment, the experimental studies done by Shyha et al. [50] showed that the use of cutting fluid such as wet cutting and spray mist could greatly reduce the burr height due to its beneficial effects on heat dissipation and thermal-influence alleviation.

Apart from the mentioned defects, geometric imperfection such as irregular hole diameter is also a critical concern for hybrid FRP/Ti drilling. Since FRP and Ti phases exhibit different thermal expansion coefficients (TEC), it makes the drilling operation more difficult to produce consistent hole diameters. In drilling, the machined holes may expand or shrink, greatly dependent on the used cutting environment. In particular, the holes produced in dry cutting condition are basically oversized due to the thermal expansion of the matrix resulting from the increased cutting temperature and the unfavorable Ti chip evacuation. Besides, the results gained by Park et al. [9] also showed that the increased tool instability due to tool wear could be another key factor contributing to the formation of oversized holes. In contrast, when wet cutting or flood coolant was employed, the generated holes of each stacked phase may be undersized due to the effective heat dissipation of the cutting fluid. Such findings were confirmed by Shyha et al. [50] when drilling Ti6Al4V/CFRP/Al7050 stacks.

In sum, despite the occurrence of various types of damage in FRP/Ti drilling, delamination induced in FRP phase and burrs produced in Ti phase are always among the most serious ones. These two types of damage often severely deteriorate the structural integrity of the machined components and result in high disassemblies and rejections. Previous studies have shown that proper

Table 5
Burr type classification for hybrid FRP/Ti drilling [50,90,91].

	Burr type A	Burr type B	Burr type C
Burr morphology [50]			 
Crack location [90,91]			

Note: (a) and (b): hole exit; (c) and (d): hole entry. (Material: Ti6Al4V/CFRP/Al-7050, T = 10/10/10 mm, θ = $[45°/0°/135°/90°/45°/0°]_S$; cutting condition for (a, d): C7 coated drill, D = 6.35 mm, n = 20/40 m/min, f = 0.1 mm/rev, dry cutting; for (b, c): uncoated drill, D = 6.35 mm, n = 20/40 m/min, f = 0.05 mm/rev, wet cutting [50]).

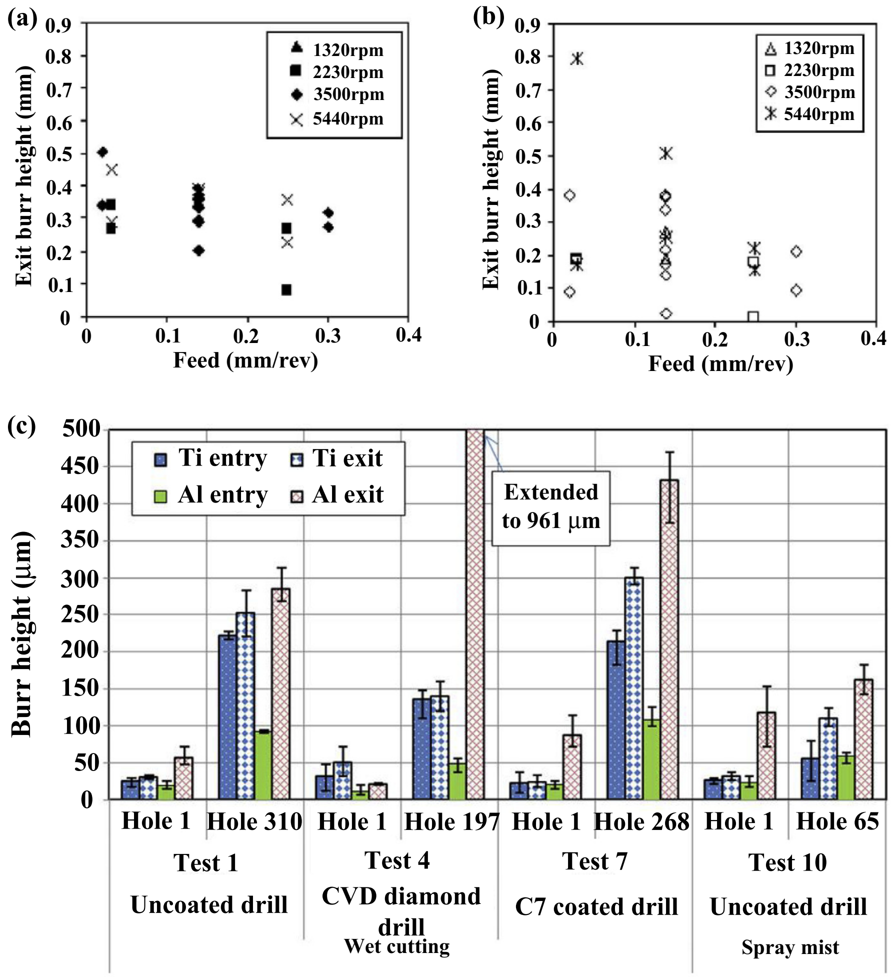


Fig. 13. Exit burr height *versus* spindle speed and feed rate when drilling thermoplastic composite/Ti stack: (a) autoclaved stack, and (b) induction heated stack. (Material: PIXA-M thermoplastic PMC/Ti, θ = [0°/90°/0°/0°/0°/0°/90°/0°]$_s$; cutting tool: C2 grade solid carbide drill) [3]. (c) Burr height results for hole entry and hole exit with different cutting tools and cutting environments. (Material: Ti6Al4V/CFRP/Al-7050, T = 10/10/10 mm, θ = [45°/0°/135°/90°/45°/0°]$_s$; Tests 1 and 4: D = 6.35 mm, n = 20/40 m/min, f = 0.05 mm/rev; Test 7: D = 6.35 mm, n = 20/40 m/min, f = 0.10 mm/rev; Test 10: D = 6.35 mm, n = 20/40 m/min, f = 0.15 mm/rev) [50].

selection of input variables (e.g., drilling parameters, cutting tool and cutting environment) would be a reasonable solution to minimizing the problems associated with drilling. The relevant illustrations will be presented in the following Section 7.

6. Tool wear mechanism

Tool wear in FRP/Ti drilling involves a series of interrelated tribological/physical consumption during the convective chip flow governing the multi-tool–work interaction. Compared to standard FRP and single Ti alloy drilling in which separated wear mode (composite-leading wear pattern or metal-leading wear pattern) operates, the mechanisms in hybrid composite drilling are usually a mixture of them but are more complex, coupled and interrelated. The rapid tool wear encountered in FRP/Ti drilling can be identified as a key problem in the bi-material cutting. Rapid tool wear and catastrophic tool failure always account for the short tool life, poor hole quality, low cutting efficiency, and high machining cost.

The geometrical changes induced on the tool active zone due to the detrimental effects from tool wear play a critical role in altering its effectiveness on generating surface finish with required tolerance. The occurrence of tool wear inevitably leads to various undesirable results, e.g., high force generation, localized heat accumulation, excessive power consumption, etc. Generally, the final wear patterns exerted on tool material in FRP/Ti drilling involve in a series of interrelated wear phenomena induced by each-phase cutting. Therefore, it is particularly difficult to clarify how much of the tool wear can be attributed to individual-phase cutting. Most of the commonly-addressed tool wear modes in FRP/Ti drilling are revealed from a global aspect. Under specific cutting conditions, wear mechanism in FRP/Ti drilling may be variable, greatly dependent on the properties of used tool material. Beal et al. [38] investigated the wear mechanisms of WC drills in CFRP/Ti cutting. It was found that the WC tool suffered severe abrasion and edge deterioration in CFRP-phase drilling while underwent excessive flank wear, adhesion wear and abrasive wear in Ti-phase drilling. Poutord et al. [48] studied the local wear of K20 type uncoated drill when dry cutting of hybrid CFRP/Ti6Al4V stack. Results confirmed that the K20 uncoated drill underwent serious Ti adhesion and edge rounding wear concerning its main cutting edges. Park et al. [46] conducted the fundamental inspections on tool wear when drilling CFRP/Ti6Al4V stack with tungsten carbide (WC) and polycrystalline diamond (PCD) drills. Abrasion, edge rounding, flank wear, adhesion wear were all detected in the stack drilling as presented in Table 6. For WC drills, the flank wear was primarily elongated by the Ti-phase drilling while the edge rounding was principally caused by the abrasiveness of the hard carbon fibers in the CFRP-phase drilling. Besides, in

Table 6
Wear mechanisms *versus* tool type when drilling hybrid FRP/Ti composite [42,43,46].

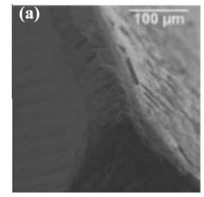
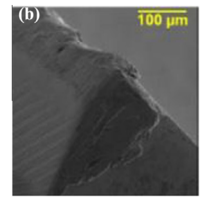
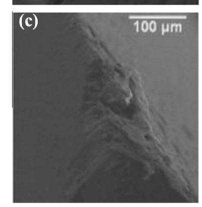
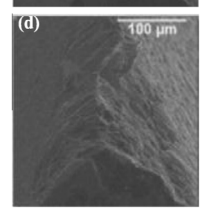
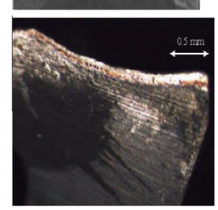
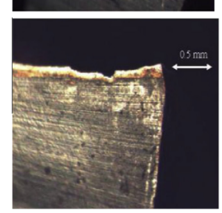
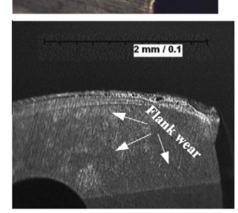
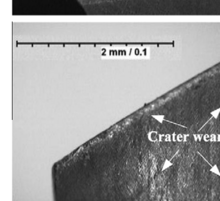
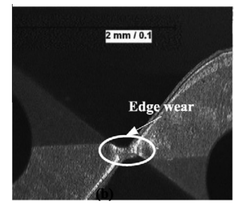
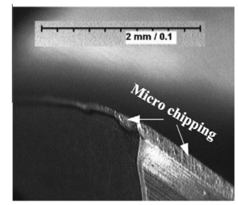
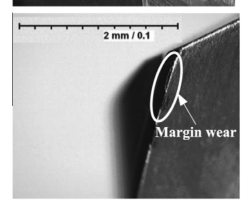
Reference	Work material and cutting conditions	Tool type	Wear morphology	Wear mechanism
Park et al. [46]	Work material : multidirectional graphite epoxy composites/Ti6Al4V, T = 7.54/6.73 mm; Cutting parameters: (a) and (b) n = 2000 rpm (CFRP), 400 rpm (Ti); f = 0.0762 mm/rev (CFRP), 0.0508 mm/rev; (a) and (b) n = 2000 rpm (CFRP), 400 rpm (Ti); f = 0.0762 mm/rev (CFRP), 0.0508 mm/rev (Ti); (c) and (d): n = 2000 rpm (CFRP), 300 rpm (Ti); f = 0.0762 mm/rev (CFRP), 0.0508 mm/rev (Ti); cutting environment: mist coolant.	WC drill (ϕ = 135° and ψ = 28°, after making 60 holes)		Edge rounding wear; Abrasive wear
		WC drill (ϕ = 135° and ψ = 28°, after making 80 holes)		Ti adhesion; Flank wear
		PCD drill (ϕ = 135° and ψ = 28°, after making 20 holes)		Edge rounding wear; Micro chipping
		PCD drill (ϕ = 135° and ψ = 28°, after making 60 holes)		Abrasive wear; Micro fracture
Ghassemieh [42]	Work material: M21ECFRP/Ti6Al4V; Cutting parameters: n = 4500 (CFRP) /1400 rpm (Ti), f = 457.2 (CFRP)/119 mm/min (Ti).	C7-coated drill (D = 6 mm)		Abrasive wear
		C7-coated drill (D = 6 mm)		Micro chipping
Isbilir and Ghassemieh [43]	Work material: T700-M21 CFRP/Ti6Al4V, θ = [90/-45/0/45]$_{5s,}$$T$ = 20/20 mm; Cutting parameters: n = 4500 (CFRP)/1400 rpm (Ti), f = 457 (CFRP)/119 mm/min (Ti).	AlTiN coated drill (D = 8 mm, ϕ = 140° and ψ = 45°)		Flank wear
				Crater wear

Table 6 (*continued*)

Reference	Work material and cutting conditions	Tool type	Wear morphology	Wear mechanism
				Edge wear
				Micro chipping
				Margin wear

CFRP-phase drilling, the absence of built-up edge (BUE) made the main cutting edges more vulnerable to become rounded and dulled when subjected to the severe abrasive-loads of carbon fibers. Ti adhesion was observed to dominate the wear mode of WC drills by covering the entire cutting edge. The PCD drills suffered relatively less Ti chip adhesion and exhibited higher wear resistance due to its superior properties. However, the PCD drills also experienced micro-chipping or micro-fracture at the cutting edges due to its intrinsic brittleness as shown in Table 6. Ghassemieh [42] studied the tool wear of C7-coated carbide drills when drilling CFRP/Ti stacks. Results confirmed that the primary wear patterns in CFRP drilling were abrasive wear, while the predominant tool failures occurred in Ti-phase drilling were micro chipping and edge fracture as presented in Table 6. Due to the adverse effects of edge chipping and coating peeling on the cutting edges, the cutter was soon deprived of the protection from the coating material and failed quickly in its rapid wear stage. Isbilir and Ghassemieh [43] carried out a comparative study of tool life when drilling hybrid CFRP/Ti composite by using AlTiN-coated carbide drills. It was concluded that the edge wear, crater wear and abrasive wear were the main wear modes governing CFRP drilling, while for Ti drilling, the key wear mechanisms were flank wear, crater wear but no adhesion wear due to the use of coolant in drilling. This was because the coolant could effectively decrease the high cutting temperature focused on the tool–chip interface and remove away the resected Ti chips on tool rake face, which minimized the Ti chip adhesion phenomenon. Besides, the occurrence of micro chipping also further exacerbated the friction between tool–chip interface, and deprived the tool substrate of coating protection, causing the final tool failure. Table 6 presents the observed wear morphologies of the used AlTiN coated drills after drilling hybrid CFRP/Ti6Al4V composite.

Furthermore, Wang et al. [52] pointed out that the overall tool wear modes involved in CFRP/Ti drilling were the combination of the edge rounding wear resulting from drilling CFRP phase and the flank wear arising from drilling Ti phase when using uncoated, AlTiN coated and nanocomposite coated drills. Moreover, the authors also highlighted that the profound interactions of each phase drilling might favor the improvement of the tool life in CFRP/Ti drilling as compared to single Ti drilling case. The main reason was due to the fact that the severe edge chipping was eliminated by the effects of carbon fibers in the CFRP phase on brushing off the Ti adhesion and smoothing the cutting edges, which substantially increased the tool life.

Although different tool materials may exhibit disparate wear behaviors when drilling hybrid FRP/Ti composite, several similarities can also be drawn. The predominant wear modes referring to abrasive wear, edge rounding, flank wear and adhesion wear are commonly confirmed by most of the existing researches concerning hybrid FRP/Ti drilling [38,42,43,45–48,51]. Table 7 then summarizes the key wear modes encountered in drilling FRP/Ti stacks with the particular reference to the used cutting conditions.

7. Strategies for high-quality drilling

The current research focus on hybrid FRP/Ti drilling is composed of the search for efficient processing techniques capable of producing high quality and excellent surface integrity. To this aim, high-quality drilling of hybrid FRP/Ti composite becomes a key pursuit in modern manufacturing community. Due to the disparate natures of FRP and Ti phases, the criteria for high-quality drilling are varied with each stacked constituent. For FRP phase, the criteria require low-extent delamination and fiber breaking, minimum hole shrinkage and low surface roughness [93] while for Ti phase the criteria are the elimination of burrs and producing excellent surface finish. The effective and direct approaches to high-quality drilling of FRP/Ti stack typically have a close relation with the cutting parameters, cutting tool and cutting environment. It is assumed that approximately 60 % of the rejections of FRP phase produced in the aerospace industry are caused by the use of improper cutting parameters, non-optimal cutting tool and unfavorable cutting environment [94–96]. Since high-quality drilling is an extremely complex and comprehensive manufacturing operation, greatly dependent on many input variables, the following section is dedicated to making a summary of the commonly-used approaches to high-quality drilling FRP/Ti stack with respect to cutting parameters, cutting tool and cutting environment.

Table 7
Summary of the wear modes dominating the hybrid FRP/Ti drilling for various drill bits and cutting conditions [38,42,43,45–48,51].

No.	Reference	Drilling condition	Tool wear mechanisms	
1	Park et al. [46]	CFRP/Ti6Al4V (T = 7.54/6.73 mm) n (CFRP): 2000, 6000 rpm; n (Ti): 300, 400, 800 rpm f (CFRP): 0.0762 mm/rev; f (Ti): 0.0508 mm/rev a. Tungsten carbide (WC) drill b. Polycrystalline diamond (PCD) drill D = 9.525 mm Coolant: cutting fluid, flow rate at 16 mL/min	WC drill PCD drill	a. Abrasive wear b. Edge rounding wear c. Severe Ti adhesion d. Flank wear a. Abrasive wear b. Edge rounding wear c. Micro chipping d. Micro fracture
2	Isbilir and Ghassemieh [43]	CFRP/Ti6Al4V(T = 20/20 mm) n (CFRP): 4500 rpm; n (Ti): 1400 rpm f (CFRP): 457 mm/min; f (Ti): 119 mm/min AlTiN-coated twist drill D = 8 mm	AlTiN-coated twist drill	a. Edge rounding wear b. Crater wear c. Abrasive wear d. Flank wear e. Micro chipping
3	Ghassemieh [42]	CFRP/Ti6Al4V n (CFRP): 4500 rpm; n (Ti): 1400 rpm f (CFRP): 457.2 mm/min; f (Ti): 119 mm/min C7-coated carbide drill D = 6 mm	C7-coated carbide drill	a. Abrasive wear b. Edge chipping c. Tool fracture
4	Beal et al. [38]	CFRP/Ti6Al4V (T = 7.54/6.73 mm) n (CFRP): 6000 rpm; n (Ti): 800 rpm f (CFRP): 0.0762 mm/rev; f (Ti): 0.0508 mm/rev a.Tungsten carbide (WC) drill D = 9.525 mm Coolant: cutting fluid, flow rate at 16 mL/min	WC drill	a. Abrasive wear b. Flank wear c. Ti adhesion
5	Park et al. [47]	CFRP/Ti6Al4V(T = 7.54/6.73 mm) n (CFRP): 2000 rpm; n (Ti): 400 rpm f (CFRP, Ti): 0.051 mm/rev a. Standard twist drill (Uncoated WC) b. Standard twist drill (BAM-coated WC)	WC twist drill BAM-coated drill	a. Abrasion wear b. Titanium adhesion c. Flank wear a. Flank wear b. Edge wear c. Coating peeling
6	Tashiro et al. [51]	CFRP/Ti6Al4V (T = 3/9.5 mm) v_c (CFRP,Ti): 18.8 m/min f (CFRP,Ti): 0.1 mm/rev a. TiAlN-coated drill b. TiAlCr/TiSi coated drill D = 6 mm	TiAlN-coated drill TiAlCr/TiSi-coated drill	a. Abrasive wear b. Flank wear a. Abrasive wear b. Flank wear
7	Poutord et al. [48]	CFRP/Ti6Al4V (T = 20.7/25.5 mm) n (CFRP): 2652 rpm; n (Ti): 265 rpm f (CFRP): 0.05 mm/rev; f (Ti): 0.2 mm/rev a. K20 uncoated drill D = 12 mm Dry cutting condition	K20 drill	a. Edge rounding wear b. Flank wear c. Ti adhesion
8	Kuo et al. [45]	Ti6Al4V/CFRP/Al-7050 v_c (Ti): 30 m/min; v_c (CFRP, Al): 120 m/min f (Ti, CFRP, Al): 0.08, 0.15 mm/rev a. DLC diamond drill b. CVD diamond drill D = 6.38 mm	DLC diamond drill CVD diamond drill	a. Abrasion b. Adhesion c. Brittle fracture d. Micro chipping a. Abrasion b. Adhesion c. Macro fracture

7.1. Cutting parameters

Cutting parameters including cutting speed (v_c) (or spindle speed (n)) and feed rate (f) locally have significant influences on the cutting responses of hybrid FRP/Ti drilling. Proper selection of cutting parameters would be beneficial for high-quality drilling of the bi-material system. The parametric effects on drilling FRP/Ti stacks have been studied by many researchers [1,3,42–44,92] as depicted in Fig. 14. Table 8 presents the used cutting conditions in the referred literature of Fig. 14. As shown in Fig. 14 (a), most of the investigations revealed that the effect of cutting speed on thrust force generation was insignificant when drilling hybrid FRP/Ti composite. In contrast, the feed rate exhibited remarkable effects on the thrust force and subsurface damage in such manner that a slight increase of feed rate resulted in the dramatically increased thrust force and deceased exit burr defect as illustrated in Fig. 14(b) and Fig. 14(c). The reasons could be explained by the fact that when feed rate increased, on one hand, the drill was required to cut off more material volume per revolution and to overcome higher cutting resistance in drilling, which resulted in

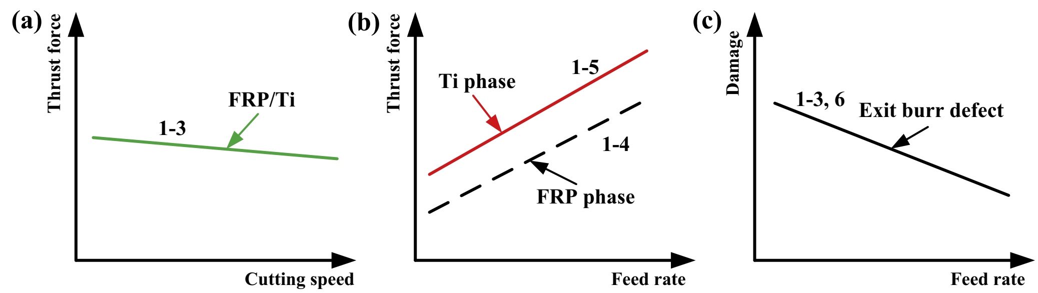


Fig. 14. Effects of the cutting parameters on thrust force and hole damage when drilling hybrid FRP/Ti composite [1,3,42–44,92].

Table 8
Work-tool materials and cutting parameters used for drilling hybrid FRP/Ti composite in Fig. 14 [1,3,42–44,92].

No.	Reference	Work material	Tool material	Cutting parameters
1	Ramulu et al. [1]	IM6-Gr/Bi-Ti6Al4V	HSS, HSS-Co, Carbide (C2 grade)	*n:* 325,660,1115,1750, 2750 rpm; *f:* 0.03,0.08,0.13,0.12, 0.25 mm/rev
2	Kim and Ramulu [3]	PIXA-M composite/Ti	Carbide (C2 grade)	*n:* 1320, 2230, 3500, 5440 rpm; *f:* 0.02,0.03,0.14,0.25,0.3 mm/rev
3	Kim et al. [92]	IM6-Gr/Bi-Ti6Al4V	Polycrystalline diamond (PCD) drill	*n:* 325,660,1115,1750, 2750 rpm; *f:* 0.03,0.08,0.13,0.12, 0.25 mm/rev
4	Isbilir and Ghassemieh [43]	CFRP (M21 T700GC)/ Ti6Al4V	Sandvik solid carbide drill	CFRP: *n:* 4500 rpm, *f:* 457 mm/min;; Ti: *n:* 4500 rpm, *f:* 457 mm/min
5	Ghassemieh [42]	CFRP(M21E)/Ti6Al4V	C7-coated carbide drill	CFRP: *n:* 3000, 4500, 6000, 9000 rpm, *f:* 355.6, 457.2, 584.2, 685.8 mm/min; Ti: *n:* 1000, 1400, 1800 rpm, *f:* 95, 119, 142, 171 mm/min; CFRP/Ti: *n:*1400,4500 rpm, *f:* 119, 457.2 mm/min
6	Kim and Ramulu [44]	IM6-Gr/Bi-Ti6Al4V	HSS, HSS-Co, Carbide (C2 grade) drills	*n:* 660, 1115, 1750 rpm; *f:* 0.08, 0.13, 0.20, 0.25 mm/rev

a dramatically increased thrust force. On another hand, the increased feed rate led to the short engagement time of the tool–work interaction. The reduced tool-work engagement time would lead to less heat generation in the Ti-phase drilling and hence reduce the exit Ti burr formation [1,3,44,92].

In addition, Ghassemieh [42] and Isbilir and Ghassemieh [43] reported that the measured thrust force and torque elevated with increased cutting speed for CFRP phase but decreased when cutting speed was elevated for Ti phase. Isbilir and Ghassemieh [43] further pointed out that the thrust force and torque produced in Ti-phase drilling were higher than that generated in CFRP-phase drilling as shown schematically in Fig. 14(b). Moreover, the induced delamination and surface roughness typically increased with the elevated feed rate in both CFRP-phase drilling and Ti-phase drilling. Furthermore, some other scholars [51,97–99] pointed out that the drilling condition including high cutting speed and low feed rate usually decreased the thrust force and minimized the delamination extent in the FRP-phase. In spite of this, Yang and Liu [37] stressed that the use of high cutting speed would inevitably increase the tool flank wear on drill bits, resulting in the rapid tool wear rate for Ti alloy drilling. Kim and Ramulu [44,100] asserted that the optimal cutting conditions for achieving high-quality machined holes should be a combination of low feed rate and low cutting speed when using carbide drills, while high feed rate and low cutting speed for HSS-Co drills when drilling hybrid composite stacks. In general, relatively high cutting speed (150–200 m/min) with low feed rate (0.01–0.05 mm/rev) is recommended for drilling composite phase in order to minimize delamination formation [101,102], while low cutting speed (10–30 m/min) with positive feed rate (0.05–0.1 mm/rev) is recommended for titanium phase machining [1,20].

To achieve high-quality drilling results, selection of optimal cutting parameters should be a direct solution. However, due to the dissimilar machinability of the stacked constituents, the ideal parametric selection for FRP phase is not the most efficient or cost effective for Ti phase and vice versa [1,44]. This leads to making a compromise in the selection of the cutting parameters that often give rise to the serious drilling consequences (e.g., high drilling forces, poor hole integrity and severe tool wear) in hybrid composite drilling [31,44,103]. Since the Ti-phase drilling always causes the biggest problems, the cutting parameter selection in drilling FRP/Ti should match that of the difficult-to-cut Ti phase. In some cases, cutting condition consisting of low cutting speed and moderate feed rate may facilitate the FRP/Ti drilling and can provide excellent hole surface finish for both FRP and Ti phases [38].

7.2. Cutting tool

Cutting tools with superior thermo-physical properties often ensure excellent tool–work interaction, provide outstanding resistance against rapid tool wear and hence offer the potential possibility for high-quality drilling of hybrid FRP/Ti composite. The selection of an ideal tool solution for hybrid FRP/Ti drilling is usually a difficult task since each-phase cutting exhibits disparate wear behaviors. For instance, when drilling FRP-phase, the cutting tool suffers severe edge rounding wear and intense flank wear due to the abrasive nature of the reinforcing fibers [104,105]. Abrasion, fracture and chipping due to thermal and mechanical loads are confirmed to be the major wear modes by most research work [104,106–108]. As for Ti-phase drilling, the serious Ti chip adhesion coupled with the high localized temperature concentrated at the tool–chip interface easily results in severe adhesion wear, edge chipping and tool fracture. Therefore, for hybrid FRP/Ti drilling, cutting tools with *(i)* high hardness, *(ii)* high toughness, *(iii)* high wear resistance, *(iv)* good chemical inertness and *(v)* high thermal conductivity are strongly preferred. Up to now, a wide range of tool

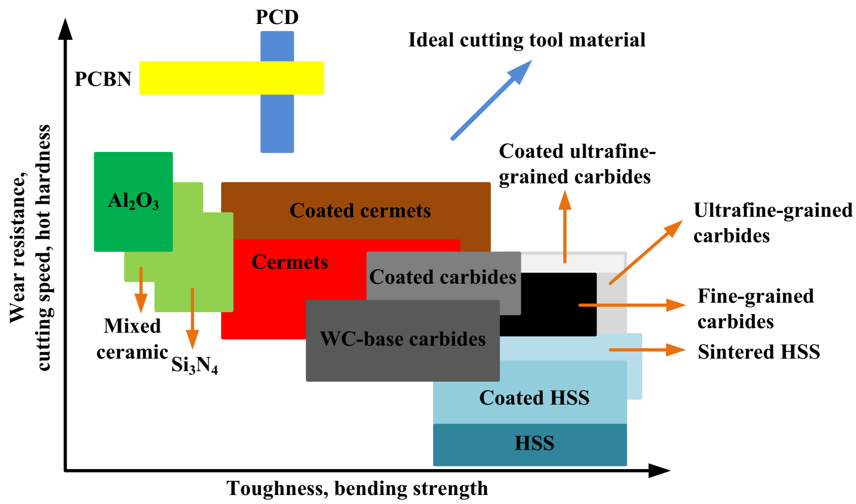


Fig. 15. Cutting performance of different tool materials used in hybrid FRP/Ti drilling [109].

materials including high-speed steel, carbide tools, coated tools, and super hard materials (PCBN or PCD) have been examined in FRP/Ti drilling as shown in Fig. 15 [109]. For commonly-used carbide tools, drills with low cobalt content are recommended for hybrid composite drilling due to their increased tool hardness and expanded abrasion resistance. For coated tools, previous researches indicated that only part of them with required properties demonstrated prominent ability to generate excellent surface finish and to yield long tool life when cutting hybrid composite stacks [46,47,50,110]. The suitability level of coated tools for hybrid FRP/Ti drilling greatly depends on the extent of their improvement on the tribological behavior of both tool–FRP interaction and tool–Ti interaction. Fujiwara et al. [111] evaluated different coated tools made of TiAlN, TiSiN and TiAlCr/TiSi coatings when drilling CFRP/Ti6Al4V stacks. Results confirmed that TiAlCr/TiSi coating outperformed the TiAlN and TiSiN coatings due to its superior wear resistance and the ability to reduce chip adhesion in the material removal process. For commonly-used Ti [C, N], TiN and Al_2O_3 coatings, several researches [112,113] indicated that they were inappropriate for FRP/Ti drilling due to their poor thermal conductivity, which would form thermal barrier against energy dissipation in the FRP-phase cutting. The polycrystalline diamond (PCD) tool was primarily reported to have superior cutting performance when machining standard FRP composites due to its high wear resistance and high thermal conductivity [114,115]. When used in FRP/Ti stack drilling, the PCD coating could also yield excellent wear resistance and effectively alleviate the serious chip adhesion encountered in Ti-phase drilling [46].

In addition, drill bits with special geometry design are also potentially qualified to conduct high-quality drilling of FRP/Ti stacks. The drill geometries are determined by a set of variables including characteristic angle (e.g., point and helix angles), edge geometry (e.g., chamfer, honed, and round edges) and tool shape (e.g., twist shape, helical shape, etc.). The excellent performance of special drill bits globally has a close relation with the mentioned geometrical variables, which results in the minimal hole damage and minor tool wear in drilling action. Xu et al. [65,106] and An et al. [116,117] compared the tool performances of one standard twist drill and one special drill (namely "dagger drill") in drilling of high-strength CFRP phase. It was found that the dagger drill promoted better surface finish, i.e., less burr defect and smaller delamination damage than the twist drill due to its smaller point angle and helix angle. Wika et al. [96] conducted several drilling trials of CFRP/Ti stacks by using four different drill bits varying in flute number and helix angle. Results showed that the two-flute drill bit with higher helix angle generated smallest cutting force and lowest cutting temperature as compared to other used drills due to its large flute volume for chip evacuation and heat dissipation. SenthilKumar et al. [49] examined the effects of point angle on tool performance when drilling of CFRP/Ti stack by using 118° and 130° point angle drills. It was concluded that the drills with higher point angle (130°) outperformed those with lower point angle (118°) from the evaluation of tool wear and chip evacuation. Furthermore, Garrick [118] argued that the drill bit manufactured with special K-land as commonly used in Ti alloy cutting, could also strength the cutting edges and hence make the tool viable for power-feed drilling CFRP/Ti stack. In the author's experiments, the veined PCD drills modified with K-land design yielded increased tool life and improved hole quality as compared to the conventional geometrical PCD drills. Recently, Kuo et al. [45] revealed that the two-stage point design for drill bit could offer improved 'self-centering' capability, thereby reducing tool deflection and guaranteeing excellent hole accuracy. Besides, it was also reported that the drill bits designed with small chisel-edge width as shown in Fig. 16, can also promote lower force generation and minimal delamination damage encountered in drilling [101].

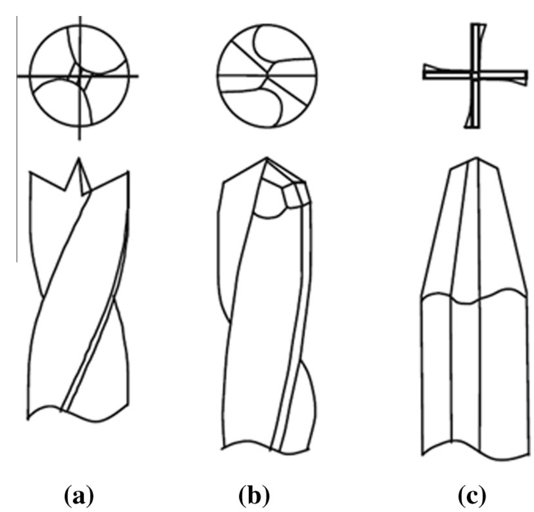


Fig. 16. Different drill bits with small chisel edge width: (a) candle stick drill, (b) multifaceted drill and (c) straight flute drill [101].

Overall, the ideal cutting tool for high-quality drilling of FRP/Ti stacks should be a good match of proper tool material and optimal tool geometry. From the aspect of tool material, drill bits with high wear resistance, high hardness, and high thermal conductivity will be of primary choice. With regard to tool geometry, despite the fact that various researches have been done for hybrid composite drilling in the past few decades, most of the work was still performed by simple comparison of special and conventional tools in terms of one or multiple aspects of drilling responses. The tool geometry design was mostly based on the empirical experience rather than the reasonable theoretical criteria. No explicit theoretical explanation was proposed to reveal the intrinsic mechanisms governing the tool geometry optimization or improvement. The detailed theoretical standards and criteria for tool geometry design of hybrid FRP/Ti drilling are urgently needed to be established in the future.

7.3. Cutting environment

For FRP/Ti drilling, proper selection of cutting environment would be another feasible approach to facilitate the high-quality machining. The use of cutting fluid in hybrid FRP/Ti drilling can globally attain the following benefits: *(i)* reducing the tool-chip frictional coefficient, *(ii)* lubricating the tool–chip interface, *(iii)* dissipating the cutting heat especially generated in Ti-phase drilling and *(iv)* removing away the chip adhesion on tool surface. For composite phase, the effects of cutting fluid primarily focus on *(i)* preventing "dust" like chip clogging on drill flutes, *(ii)* reducing force generation and cutting temperature on tool–chip interface; and *(iii)* improving the machined surface quality of the FRP phase. Several researches have proven that the use of cutting fluids in hybrid composite drilling could greatly improve the machined hole quality and expand the tool life as compared to the dry cutting environment. Brinksmeier and Janssen [2] compared the minimum quantity lubrication (MQL) and dry cutting environment when drilling $AlCuMg_2$/CFRP/Ti6Al4V stack. It was found that the MQL significantly reduced the chip adhesion on hole surface and generated better hole quality (especially tight diameter tolerance) than the dry cutting condition. Besides, the use of MQL also prevented the BUE formation on tool faces and hence alleviated the tool wear rate. Furthermore, Fujiwara et al. [41] asserted that the drill bit used under water-mist-cooling process could also yield longer tool life than under dry cutting condition when drilling CFRP/Ti6Al4V stack. The use of water mist effectively decreased the force generation, reduced the chip adhesion and promoted tight hole diameter in contrast with the dry cutting condition.

The beneficial effects of cutting fluid on drilling action are critically dependent on its delivery type (e.g., flooding, spraying, misting, etc.), especially on its access level to the tool-chip active zone. Shyha et al. [50] conducted several drilling trials of Ti6Al4V/CFRP/Al-7050 stacks by employing three different fluid-delivering methods referring to flood coolant (through spindle spray), wet cutting and spray mist. Results showed that both the flood coolant and wet cutting produced undersized holes with the deviation of 14 μm and the maximum error of -20 μm, respectively. In contrast, the spray mist environment gave rise to significantly oversized holes with the tolerances increased from 80 μm at the first hole to 120 μm when the drill was totally worn out. The use of high pressure through spindle made flood coolant generate the best roundness and lowest surface roughness due to the improved lubricant/coolant access to the tool–chip interface. Therefore, in order to maximize the benefits of cutting fluid, through-spindle coolant system (also known as through-tool coolant system) should be recommended in hybrid FRP/Ti drilling since it can deliver fluid through spindle and tool passages directly to the cutting zones.

However, the use of cutting fluid inevitably results in severe damage to the environmental and work environmental sustainability due to the substantial content of chemical additives, which are more or less toxic to human health. To solve the problem, near-dry cutting has drawn due attention in ecologically machining of hybrid FRP/Ti composite. This is because the near-dry cutting preserves the environment with combined impacts of ecological and economic. For instance, MQL drilling considered as a near-dry cutting is assumed as a promising necessity for hybrid composite machining. The MQL technique involves the use of a small amount of biodegradable oil droplet dispensed to the tool–chip interfaces by compressed air flow, which can greatly reduce cutting temperature, improve surface quality and expand tool life [8,119,120]. Since the small quantity of used biodegradable oil is less waste polluted, decomposable and non-toxic, the MQL solution can be successfully applied to fulfill the demands of environmental and work environmental sustainability when machining hybrid FRP/Ti composite. Brinksmeier and Janssen [2] employed the MQL machining method in drilling Ti/CFRP/Al stack aiming at realizing economical drilling of multi-phase materials. Different cutting fluids and supply strategies were utilized in drilling. The use of MQL with internal supply produced the tightest diameter tolerances as compared to the conventional dry cutting condition. Serious BUE adhesion and tool flank wear were clearly reduced once MQL was applied. The MQL technique exhibited a suitable solution for realizing high-quality production of the stacked composite material.

Although limited open literature [2,41,50] is reported to employ cutting fluid in hybrid FRP/Ti drilling, the use of cutting fluid indeed demonstrates excellent prospects to improve the machinability of the material. For proper selection of cutting fluid, comprehensive consideration of both manufacturing process (e.g., fluid type, cost, delivery type) and human/environmental impacts should be seriously taken. With regard to the near-dry cutting, in some cases, even though it is confirmed to be beneficial for hybrid composite drilling from an ecological and economic viewpoint, proper steps are still required to be taken in order to make this technology more environmentally friendly and cost efficient.

8. Concluding remarks

In the past few decades, much progress has been achieved concerning hybrid FRP/Ti composite drilling and has led to a better understanding of the cutting physics activated in machining. This paper presents a rigorous review of various investigations in the existing literature in terms of force generation, cutting mechanisms, drilling-induced damage, etc. Based on the comprehensive analyses, some key conclusions on current state-of-the-art and several prospects on future work can be drawn as follows.

- Drilling hybrid FRP/Ti composite involves interrelated cutting behaviors and coupled chip-separation modes due to the disparate natures of the composite/metal system. Compared to the FRP-phase and Ti-phase drilling, the interface drilling could be considered as the most complex and challenging operation due to the multi-tool–work interaction dominated and the severe transfer of mechanical/physical responses occupied. At present, the in-depth cutting physics governing FRP/Ti interface drilling is still significantly understudied, future work is expected to address deeply the issue.
- Hole damage induced in hybrid FRP/Ti drilling comprises both the polymeric imperfections and metallic defects. Among them, the interface damage is usually the most serious one. The delamination damage promoted in FRP phase and the burr defect occurred in Ti phase are regarded as the key problems

encountered in actual production since these two damage types often lead to poor assembly tolerance and high rejection of the machined components.

- Tool wear mechanisms controlling FRP/Ti stack drilling are usually the coupling and interaction of both composite-leading and metal-leading wear modes. Despite the wear discrepancies among different drill materials, abrasive wear, edge rounding wear, flank wear and adhesion wear are typically the predominant wear patterns governing the tool wear progression from a global perspective.
- Potential approaches to high-quality drilling of FRP/Ti stack were discussed in detail versus cutting parameters, cutting tool and cutting environment. The high-quality drilling, however, is a comprehensive and interactive manufacturing operation, dependent on many internal-external factors like tool material/geometry, drilling parameter, cutting environment as well as the workpiece properties and the used machine tool. To achieve high-quality results, profound expertise and rich experience based on the mentioned issues are required to propose a superior tool-external-factor configuration for hybrid FRP/Ti drilling.
- In the current state, through the rigorous literature survey, significant scientific advances have been achieved based on the experimental studies of hybrid FRP/Ti drilling. However, relatively limited publications were found in the open literature dealing with the numerical studies of hybrid FRP/Ti drilling [4,5]. Actually, the numerical approach should be a promising tool that can significantly help to optimize the mechanism investigations when drilling this multi-phase material. In the future, the combined experimental and numerical studies are urgently demanded to address precisely the physical issues involved in hybrid FRP/Ti drilling.

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